DOCTOR OF PHILOSOPHY

SUBSEE

An exploration and development of the 3D visualisation and grading of subsea survey data

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Award date:
2020

SUBSEE: An exploration and development of the 3D visualisation and grading of subsea survey data

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Submitted in fulfilment of the
requirements for the degree of
Doctor of Philosophy

Duncan of Jordanstone College of Art & Design,
University of Dundee
in collaboration with
3DVisLab
ADUS DeepOcean

June 2020

For Team Gauld

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Abstract

High-resolution subsea surveying offers new opportunities to explore difficult or hazardous underwater environments and, when using multi-beam sonar, provides three-dimensional bathymetric data for visualisation. The primary focus of this practice-led research is whether the 3D visualisation and grading of subsea survey data can be developed beyond current industry practices. Three commercial case studies and their resulting datasets were used: *Troll*, an oil and gas field near Norway; *Greater Gabbard*, an offshore wind farm near England; and *Gullfaks*, an oil and gas field near Norway.

This investigation is structured using the author's *Explore Review Create* methodology – an iterative multi-method approach with contributory elements including action research and reflective practice. The research is supported by an exploration and review of relevant literature, comparing existing visualisation techniques and identifying a lack of consistency in evaluating or grading subsea survey data. Three case studies follow, presenting and evaluating the application of a variety of 3D visualisation techniques including some which go beyond those readily adopted in the offshore industry, such as the use of 3D printing. Finally, a fourth research chapter examines how the state of data can be assessed and proposes a scale by which future data could be graded – the DUNDEE DATA GRADING SCALE.

The author proposes that the work undertaken during each of these three case studies provides new knowledge in improving the application of 3D visualisation techniques to subsea survey data. As a result of this new knowledge, the DUNDEE DATA GRADING SCALE is offered as a first step towards improving data capture and quality awareness by providing an improved understanding of what will be required to produce quality 3D visualisations from each dataset, with additional clarity in how to achieve this by applying a broader range of visualisation tools.

Glossary

This research discussed in this report is considered interdisciplinary in nature, and the usage of some terms can vary across different fields. For clarity, the glossary below explains how these terms have been adopted and used throughout this document.

3D Printing	The process of making three-dimensional solid objects from a digital model. These are typically created using a process called additive manufacturing where successive layers are printed on top of one another to create the finished object.
3DVisLab	A team of researchers based at the University of Dundee, working on the research and development of visualisation in both subsea and other industries.
ADUS DeepOcean	A company specialising in high-resolution surveys of man-made structures which are totally or partially submerged. These include shipwrecks, wind turbines, oilrigs, debris fields, assets related to energy production, and submerged archaeological sites.
Anaglyph 3D	A means of presenting stereoscopic three-dimensional images using different colours to encode each eye's image, typically red and cyan. Each image is slightly different and creates the illusion of depth in an image or video.
Bathymetry	Originally, the ocean's depth relative to sea level, though now refers to the study of underwater terrain, by indicating measured depths below sea level (often shown through contour mapping).

Boolean In 3D modeling, a method of combining polygonal shapes using add, subtract and intersect operations, as if they were building blocks (Autodesk, 2020).

CloudCompare Open source software used for viewing and processing digital point cloud data, typically in XYZ format.

Data Typically raw, unorganised numbers or facts that need to be organised, processed and presented to have any meaning (Diffen, no date).

DJCAD Duncan of Jordanstone College of Art & Design, part of the University of Dundee.

DJCAD Make A digital fabrication facility, providing access to equipment such as laser cutters and 3D printers.

EPSRC Engineering and Physical Sciences Research Council.

EVA Electronic Visualisation and the Arts, an annual conference based in London with a focus on the development and application of visualisation technologies.

Fledermaus Industry leading software by QPS for interactive geospatial processing and analysis, with a particular relevance to offshore and hydrographic applications.

Geospatial Relating to the relative position of things on the earth's surface, such as GPS or satellite imagery.

GIS A geographic information system (or GIS) is a system designed to capture, store, manipulate, analyse, manage, and present spatial or geographic data.

Hydrography The science that measures and describes the physical features of bodies of water and the land areas adjacent to those bodies of water.

Information The result of the interpretation and processing or structuring of raw data, creating new understanding where previously there may have been none (Diffen, no date).

ISHAPS Independent Sonar Head Attitude and Positioning System, an innovative method of deploying subsea survey equipment developed by ADUS DeepOcean, designed to minimise errors in data acquisition.

Maya Commercial software by Autodesk, used to undertake 3D computer animation, modeling, simulation and rendering.

MBES Multi-Beam Echo Sounder, a sonar device which emits multiple 'beams' creating a wider area of coverage in gathering underwater depth information.

Morphology In archaeology, the study of the shapes or forms of artefacts, such as the seabed.

Open Data Data that can be freely used, reused and redistributed by anyone, without restrictions from copyright, patents or other mechanisms of control (Open Data Handbook, no date).

Open Source Something that is made freely available and can be modified, changed and improved. In the case of software, usually the source code is made available (Open Source Initiative, 2007).

Photogrammetry The use of photography in surveying and mapping to ascertain measurements between objects. Commonly used to reconstruct three-dimensional objects or locations from a series of photographs.

Point Cloud A series of data points or coordinates in three-dimensions, usually labelled X, Y and Z.

Rendering In computer graphics, the process of creating a 'final' image from a 3D scene built using computer graphics and animation. Usually includes the complex textures, light, and shading that are not applied whilst working on the content.

RGB Refers to the system of colours created using varying amounts of Red, Green, and Blue.

Rhino Commercial 3D computer graphics and animation software which can be used to create and edit three-dimensional models.

RTK GPS Real-Time Kinematic satellite navigation is used to enhance the prevision of GPS (Global Positioning System) information, often to centimetre-level accuracy.

ROV Remotely Operated (underwater) Vehicle, a highly manoeuvrable underwater robot operated by a person on the surface. Often used to explore or survey difficult or inaccessible locations.

Scour Scour is the removal of sediment, such as sand or rocks, from around an underwater object, such as the base of a wind turbine. Scour is caused by swiftly moving water, and can 'scoop' out foundations, compromising the stability and integrity of a structure (USGS, 2016).

Side-scan A type of sonar device, usually towed behind a vessel, used to capture seabed imagery. Can be used to survey a large area relatively quickly, but does not provide depth information.

SONAR SOund Navigation And Ranging, a type of acoustical imaging used to gather information about objects and locations underwater.

Stereoscopy A technique used to create the illusion of depth in an image or video, by presenting a different image to each eye. The brain combines these, giving the perception of 3D depth.

Surface model A way of creating and representing objects, giving them a solid look and feel. Surface modeling is widely used in a variety of industries, including architectural renderings and video games.

Surface normals A vector (which cannot be seen or rendered) that is perpendicular to the surface at a given point, usually the centre. This creates a 'facing' for each surface which has a surface normal.

Visualisation The process of making data or information visible, whilst improving both aesthetics and clarity where possible. It can enable new discovery of patterns, trends and correlations that may have previously gone unnoticed in a different, less effective, format.

WreckSight Shipwreck visualisation application by ADUS DeepOcean used to view, measure and explore processed point cloud data.

Declaration

This thesis is the work of Dylan Gauld and the author is solely responsible for the contents. Unless otherwise stated, all references cited have been consulted by the author of the thesis.

The contents of this thesis have not been submitted for any other higher degree.

Dylan Gauld
MSc, BSc (Hons)

Acknowledgements

Every PhD journey is a unique experience, and just as challenging as it is rewarding. It can at times be frustrating, lonely, invigorating and exciting, though more often a mix of all of these things at any given time. I am fortunate enough to have been able to share my journey with a whole team of people, and I am confident that you would not be reading this thesis without their strength and guidance along the way.

I would like to first thank my supervisors, Professor Chris Rowland and Professor Jon Rogers, and both Professor Mary Modeen and Fraser Bruce as advisors, for their support throughout my studies. They have channelled my ideas, nurtured my creativity and pushed me when I needed it most. They have helped open doors, shown me how to be a good researcher, and most importantly, encouraged me to *just keep swimming*, for which I am truly grateful.

I would also like to acknowledge and thank Dr John McGhee, for without his direction, enthusiasm and support I would not have discovered visualisation or undertaken this *adventure of incredible proportions*.

ADUS DeepOcean have also played an instrumental role in my doctoral studies – not only providing data for visualisation, but also welcoming me as part of their team on live projects. I would especially like to thank Mark Lawrence for this opportunity – without the generous support from ADUS DeepOcean, undertaking this PhD would simply not have been possible.

In addition to the ADUS DeepOcean team, I would like to take a moment to thank everyone from DJCAD who has helped me throughout my PhD studies – administrators, makers, technicians and more. You have all contributed to my journey, and I wish you all the best in your own.

I would also like to acknowledge the vital contribution of the University of Dundee's Counselling Service – undertaking this research has consistently pushed me beyond my limits and without their support I most likely would have lost sight of the finish line completely.

And finally, I would like to thank all of my family and friends who have been there for me over the last few years. In particular my mother Lesley, who not only helped me shorten my sentences and make sense of what I was trying to say, but who has always been there when I needed it – cheering me on through the blizzard when I had lost sight of the peak. I would like to thank my brother Rhorry for letting me show him who was the best at Monopoly, but also for completing his expedition first – so that I could learn from his experiences and avoid some of the pitfalls (or tree-swings) along the way. Special thanks go to my grandparents, who have listened eagerly to my presentations and generously offered support throughout. Thanks also go to Caz who provided welcome distraction when I needed it the most, and to Tony, Vanessza, and the rest of the DUFC fencers who reminded me that I'm not as young as I used to be.

Last, but by no means least, I would like to thank Captain and Roland for telling me when to stop writing, and of course, Laura for being my guiding light, reminding me of the best in people, and for making me eat my vegetables.

Without the continued support from each and every person, this journey would have been considerably tougher, and so I owe my success and achievement to you all.

Preface

Growing up, I was always interested in drawing, technology, and building things, although usually as individual activities. I was fortunate enough to have both encouragement and support in developing these interests, which included amassing a large collection of Lego, K'Nex and Meccano. I also attended art classes in various locations, which nurtured my creativity and developed both my visual and spatial awareness. Although I did not realise this at the time, these were all skills that would later become essential in traversing the path I now find myself navigating through research.

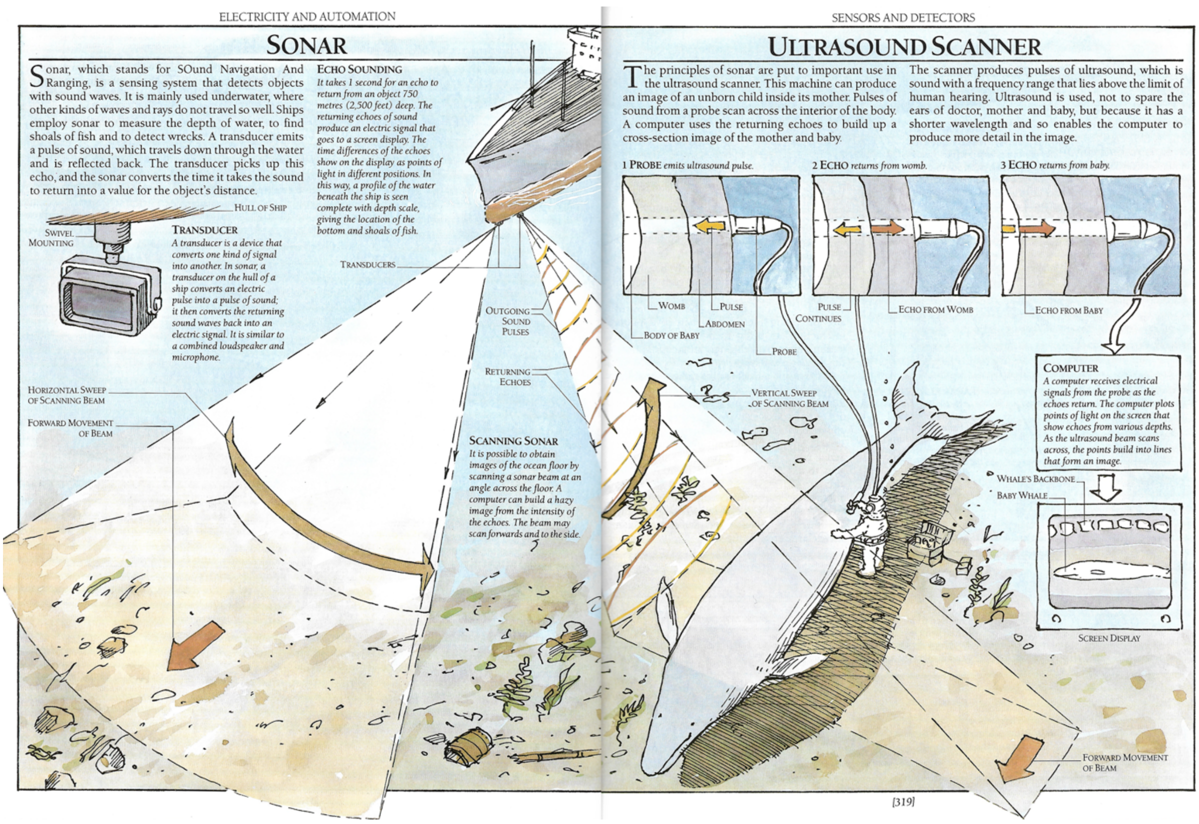

Figure 0.1: Scanned extract describing sonar, from The Way Things Work by David Macauley (1988)

Somewhere during the late 1990s, I was given a book as a gift. This book was titled *The Way Things Work*, written by David Macauley and originally published in 1988. It was written as a learning tool, to help teach readers about the application of scientific principles, and how they are often used in everyday objects and scenarios. However, what set this book apart from others I have read is the visual way in which each principle is explained… by using woolly mammoths to act these scenarios out! At first glance this may seem an entirely pointless gimmick, but on further (and more recent) inspection, was actually a very clever approach – luring readers into the concepts with fun and interesting imagery and narrative, whilst teaching them something quite useful and important in the process (often without an awareness of this happening!). On reflection, I now understand this practice as visualisation.

Many years later, I attended Edinburgh Napier University, as a student on their negotiated Information Technology programme. As one of my module choices, I opted for an introduction to 3D computer graphics and animation – something I had never had the opportunity to try my hand at previously. As soon as I started the module, I realised I had found something that motivated me and that I was passionate about. I transferred to their Digital Media programme, where there were greater opportunities for me to study and practice animation, both 2D and 3D. At the time, just like the other students I was learning alongside, I was working towards a career in the visual effects or games industries – explosions, car chases, superheroes, and the excitement and energy of working on these types of projects… what could be more exciting?

However, during my final year, still being relatively new to animation, I realised that passion alone would not be enough to get me there and so I applied for a number of postgraduate courses at different art colleges. I accepted a place at Duncan of Jordanstone College of Art & Design, where I could invest in developing my animation skills further. Within only weeks of starting my studies, I had been exposed to new, innovative and exciting uses for computer graphics and animation – visualisation of medical, scientific and bathymetric data. The idea of creating something that would generate new knowledge and understanding was far more exciting to me than the prospect of working on films and games.

Discovering visualisation created a new motivation in me, realising I had an opportunity to contribute to new research, with my work making a significant positive difference to the lives and experiences of others. I spent the next year working with mathematicians, who were using complex mathematical models to try and predict the aggressive growth and development of tumours. Showing this growth over time, I used animation to visualise their numerical data in three dimensions, allowing the mathematicians to 'see' their data in a way they had not been able to, whilst also reaching new non-specialist audiences (Figure 0.2). It proved to be fascinating to some and terrifying to others, but unanimously useful in both revealing and explaining something that previously could not be seen with the human eye.

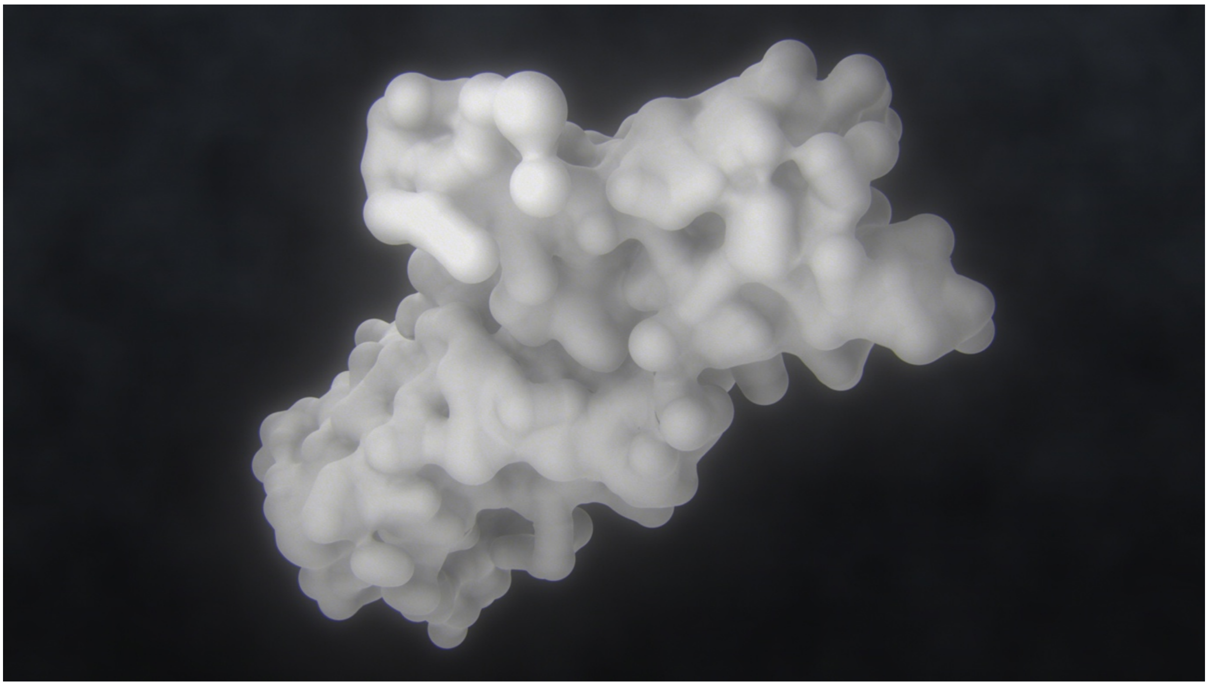

Figure 0.2: Still taken from short film 'Growth' (Gauld, 2011)

Beyond my postgraduate studies, I worked on a variety of projects – visualising pathogen spread in hospital wards, explaining how the correct treatment of asthma can allow for 'normal' physical activity, and re-constructing Magnetic Resonance Imaging (MRI) data in three-dimensions. These projects allowed me to develop my understanding of visual communication, and build a broader experience of visualising different types of data. It also introduced me to visualisation research, and in particular, how to approach and undertake this successfully.

Most recently, I was given the opportunity to work on visualising subsea survey data, forming the basis of my doctoral studies.

As I once started doing many years ago, I continue to draw, build and create.

1 Introduction

> "Data presentation can be beautiful, elegant and descriptive. There is a variety of conventional ways to visualize data – tables, histograms, pie charts and bar graphs are being used every day, in every project and on every possible occasion. However, to convey a message to your readers effectively, sometimes you need more than just a simple pie chart of your results." (Friedman, 2007)

Visualisation is defined as two things: the "formation of a mental image of something", or the "representation of an object, situation, or set of information as a chart or other image" (Lexico, no date-d). Although this doctoral research is built upon the latter idea of representation, both are equally as important, as any visual practitioner must imagine and form an image of what they are going to create before they can attempt to fully realise it.

The use of visualisation techniques to depict information and data has been practiced for hundreds of years, and is still considered to be a craft – something that takes practice, dedication, and skill to generate meaning and insight where there was none. With a long history of research and development, there are now a wide variety of ways in which information can be communicated visually.

In contrast, using 3D computer graphics and animation to visualise subsea survey data is still considered to be in its infancy, with a limited (though steadily increasing) amount of research contributing new knowledge. In the subsea surveying industry, many companies still rely on older, more traditional visualisation methods, such as using two-dimensional paper-based charts and diagrams, to convey complex technical information.

The goal of this practice-led doctoral research is to investigate and develop the application of new 3D visualisation techniques to subsea survey data. The author will explore, review and create visualisations using the latest methods, and the research will be directed by a primary research question:

> **Can the communication and understanding of subsea survey data be improved by using 3D visualisation methods**?

To help in answering this question, a series of sub-questions were also developed, and Chapter 2 discusses these in greater detail. Each of these questions are re-visited throughout the research case studies to ensure that focus is maintained and to provide clarity on the work as it progresses towards answering the primary research question.

Chapter 3 introduces five themes that emerged throughout the ongoing research and helped shape and define the work being undertaken. These have been mapped to each of the case studies showing the overall researcher position, and to also provide a clearer view of the individual relevance of each of the case studies. Though these five themes are each directly relevant to the visualisation of subsea survey data, their resulting outcomes can be applied elsewhere, offering new insight across different types of dataset (such as those captured using laser scanners instead of multi-beam sonar).

A review of relevant literature was undertaken which contributed significantly to the knowledge and understanding of critical areas including visual communication, visualising information and data, collecting subsea survey data and the use of emerging visualisation techniques. This is presented as two interdependent chapters, providing background research (chapter 4) and a multi-method contextual review (chapter 5). The work undertaken during this part of the research process provided a key foundation of knowledge, exploring industry practices and informing each of the case studies that would later be completed. As the industry partner only used particular processes and technologies (such as multi-beam sonar), these chapters address this limitation by broadening the exploration of modern visualisation and its associated challenges, creating an opportunity for knowledge to be shared across disciplines and further informing the author's research process. Visualisation topics such as metadata and paradata are explored, and reasons for their noticeable absence in subsea surveying are explained.

Chapter 6 starts by introducing the author's methodological framework, titled '**Explore Review Create**', used throughout this doctoral research. This chapter explores each of the contributory methodological elements used in creating and tailoring a suitable multi-method approach for 3D visualisation research.

As the first of three case studies, Troll (Chapter 7) has a focus on visualisation, and explores and compares different techniques to see which can offer the greatest communicative value. This includes data presentation methods currently used in subsea surveying (typically behind current techniques and technology) and some which have emerged more recently and are being used in other industries. A series of workshops explores which of these 3D visualisation outputs could offer the most understandable visual results, and whether the most complex outcomes are worth the additional investment.

Chapter 8 explores the second case study, Gabbard, and builds on the realisation that visualisation alone is not enough. The quality of both data acquisition and processing contribute significantly to the creation of 3D visualisations and therefore good quality data should be considered an essential part of a complete workflow. The Gabbard study includes a commercial placement on a project surveying one of the UK's largest offshore wind farms, which informed knowledge of current industry practices, primarily around sonar equipment and acquisition. In addition, through processing live data, this project provided a library of high-resolution survey data which could later be used throughout this doctoral research.

Gullfaks, the third case study (Chapter 9), develops this notion of having good quality data further by tackling a poorly acquired dataset – one that is missing critical positioning information. Through the application of advanced processing techniques, this commercial project shows that data which had been previously unusable can be recovered to some extent, but that it is significantly easier to carefully consider the whole process of acquisition, processing and visualisation in the first instance.

A fourth research chapter (Chapter 10) details the creation and evaluation of an original visualisation grading scale – the *Dundee Data Grading Scale* (or *Dundee Scale* for short). This development builds on the knowledge gained throughout each of the three case studies and examines how the state of data can be assessed, resulting in a proposed scale as a first step towards informing data capture and improving quality awareness in this challenging data domain.

Finally, Chapter 11 provides a summary of all of the research undertaken, the reflection throughout, and conclusions in the form of findings and new knowledge generated. It also discusses ideas for future research beyond the scope of this doctoral research, but which are still relevant and require further work to be undertaken.

1.1 Led by research practice *and* commercial practice

In recent years, there has been an increasing amount of interest in design PhDs (Yee, 2010). This has been responsible for transforming the traditional research approach, and developing and changing the ways in which design research is being undertaken. Yee (2010) highlights four key characteristics of an evolving design-based research thesis:

> "the format and structure of the thesis, a pick-and-mix approach to research design, situating practice in the inquiry, and the validation of visual analysis".

The author has considered each of these characteristics, and accordingly this doctoral thesis should be considered a practice-led hybrid approach to research – one which is not traditional, though not *entirely* practice-based either, and is suitable for design-based research. The author's methodology embraces a 'pick-and-mix' approach, and is discussed fully in Chapter 6. The commercial nature of the research case studies encourages 'real-world' practical inquiry, where problem solving is tested outside of a controlled laboratory environment (section 6.1.7). With visualisation forming the basis of this research, visual analysis and validation has been essential and industry experts were consulted as part of this (presented and discussed throughout, with a complete set of responses found in appendix 14.4).

This research has been led by practice, using case studies to document commercial projects, and is intended to explore and improve the creative and technical practice (both digital and physical) in the thesis subject area – the 3D visualisation of subsea survey data gathered using multibeam sonar. As a result, the presentation and discussion of the research practice has been fully integrated into the thesis body and accompanying commercial datasets are referred to throughout. Specific datasets are cross-referenced with a 'folder' icon (an example of this is shown in Figure 1.1) and have a caption providing a specific file or folder location.

Figure 1.1: Folder icon indicating data files which can be found in the accompanying data repository

These files are provided as part of a supplementary data repository and form a significant part of the creative practice. A set of newly-developed scripted tools are also referred to throughout, and these are provided in appendix 14.2 (Appendix II: Visualisation tools).

It is important to note that the commercial practice has been undertaken as part of collaborative live projects, and each includes varying contributions from the author, ADUS DeepOcean, and the 3DVisLab. The specifics of each of these contributions are defined as part of each case study.

1.2 Access to datasets

As part of the research case studies, commercial subsea survey datasets were acquired, processed and visualised. Ownership of these datasets remains with the original companies for which the work was undertaken by ADUS DeepOcean. With permission from ADUS DeepOcean, these confidential datasets have been made available to the author for research purposes and are used and discussed throughout each of the associated chapters.

Open access to the datasets has not been granted and these are currently protected by non-disclosure agreements with the University of Dundee. Limited access can be approved in some circumstances, and the complete datasets have been provided alongside this thesis for examination purposes.

Further information on accessing and using these datasets can be found in appendix 14.1 (Appendix I: Supplementary datasets).

2 Research Questions

In this section, the author's research questions will be presented, starting with the primary research question, titled 'RQ0'. This single question will be used to define the overall direction of the research in conjunction with both the contextual review and research activities.

In addition to question 'RQ0', a need was identified to break this into a series of smaller sub-questions, RQ1-4, which are detailed below.

RQ0: Can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?

> **RQ1:** How effective are current visualisation methods in communicating subsea survey data accurately and clearly?
>
> **RQ2:** What is the relationship between automation[1] and 3D visualisation of subsea survey data?
>
> **RQ3:** What are the effects on the understanding of subsea survey data in the transitioning between digital and physical 3D representations?
>
> **RQ4:** What is the measurable value of innovation in 3D visualisation to the subsea surveying industry?

---

[1] Throughout this thesis, automation refers to the improvement of tasks using computer processing techniques, which were previously undertaken manually. It is defined as a research theme in chapter 3, and further discussed throughout each of the related case studies.

These questions were developed throughout the course of this doctoral research, and helped direct the research activities. Research question 1 was important in building a better understanding of the current visualisation methods being used, where research questions 2 and 3 looked beyond these. Research question 4 was included to ensure the research activities continued to maintain a commercial relevance.

3 Research Themes

Throughout each of the case studies presented in the following chapters, a series of research themes started to emerge – these have been used to help maintain focus on the most relevant topics. Awareness of these themes has contributed to creating a cycle of feedback where the research activities have informed and improved the research questions, which in turn directed the developing research practice and themes. These key themes are summarised visually in Figure 3.1, followed by a further explanation of each theme.

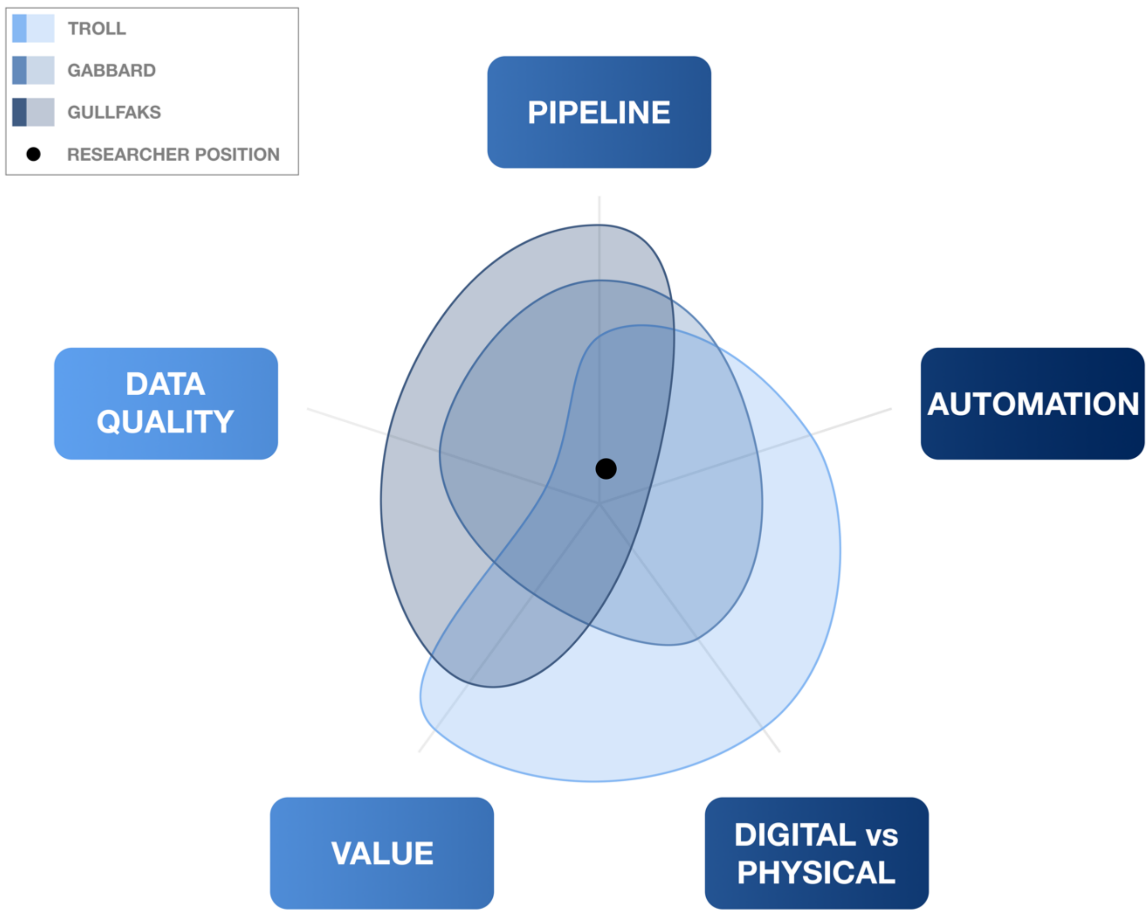

Figure 3.1: Case study relevance mapped to research themes

By combining both Venn and star diagrams, this image measures and compares the relevance of each of the three case studies to the research themes, and highlights the area of overlap between each of them. The central overlapping segment (marked with the black dot) shows the resulting researcher position amongst the themes that have emerged. In a perfect research scenario, where all of the themes were addressed equally, this would converge on 'zero' where the axes meet – however, this diagram is intended as an indication of the actual research conducted and not an ideal to be adhered to.

Understanding **Pipeline** (or workflow) refers to the working processes of visualising subsea survey data – which the author has summarised as acquisition, processing and visualisation in section 4.5 (and shown in Figure 4.5). By better understanding the visualisation workflow, stages can potentially be improved or quickened (or even skipped in some cases) in an attempt to create stronger and clearer visual outputs in the best possible way.

The application of **automation** to improve visualisation is of great importance, and can be used to speed up complicated procedures such as the automatic creation of surface models from point cloud data, or provide relief from simple and repetitive tasks such as the removal of point cloud noise during processing. However, there are a large number of elements which are not currently automated, and instead rely on human input despite often being immensely time consuming – a better understanding of the significance of this within the relevant industries will be required. An important and relevant question is considering whether something *should* be automated rather than if it *can* be – in the visualisation community, there is a growing belief in the continued application of tacit knowledge, gained through first-hand experience of working with a variety of data.

Digital versus physical addresses the notion that we should be using physical representations of data which was originally physical. As is often the case, subsea survey data is gathered in three-dimensions (typically at great expense) and then presented using only two-dimensions. There are benefits to both approaches, and part of this doctoral research is comparing the difference between on-screen and beyond-the-screen.

Value continues to be an important, challenging, and somewhat vague element of visualisation. There is no absolute definition for value, as different fields have different requirements, expectations and successes – what may be valuable to subsea surveyors is unlikely to be valuable to forensic dentists, for example. At its core, however, there are elements that are measurable, such as the communicative value of visualisation, and defining these in a more structured and understandable way forms part of both this and future research.

Data Quality is a critical consideration in the visualisation process – without 'good' data, it becomes significantly more challenging to produce effective visualisations. Companies such as ADUS DeepOcean have a series of factors which they address during data acquisition, but these are for surveyors and there is no measurable equivalent for subsea visualisation. As a result, considerable time is often spent trying to salvage datasets which yield very little in the way of useful results. If data could be assessed or graded in a more formal manner, it would give a clearer indication as to what is achievable before time and money are committed.

It is also important to note that whilst these are identified as individual themes, they each form part of the wider topic of visualisation research, and work undertaken may address more than one theme simultaneously (for example, the workshops undertaken during the Troll case study consider both *value* and *digital versus physical* visualisation techniques). Additionally, the order in which these themes are presented is not indicative of the order they will be addressed, largely due to the dependency on subsea survey data being made available for research purposes.

Finally, Figure 3.2 shows the relationship between research sub-questions and themes. Research question zero was not included in this diagram, as all of the themes contributed to answering this. Solid lines show the most significant connections, with dashed lines denoting a lesser, though still important, contribution to each research question.

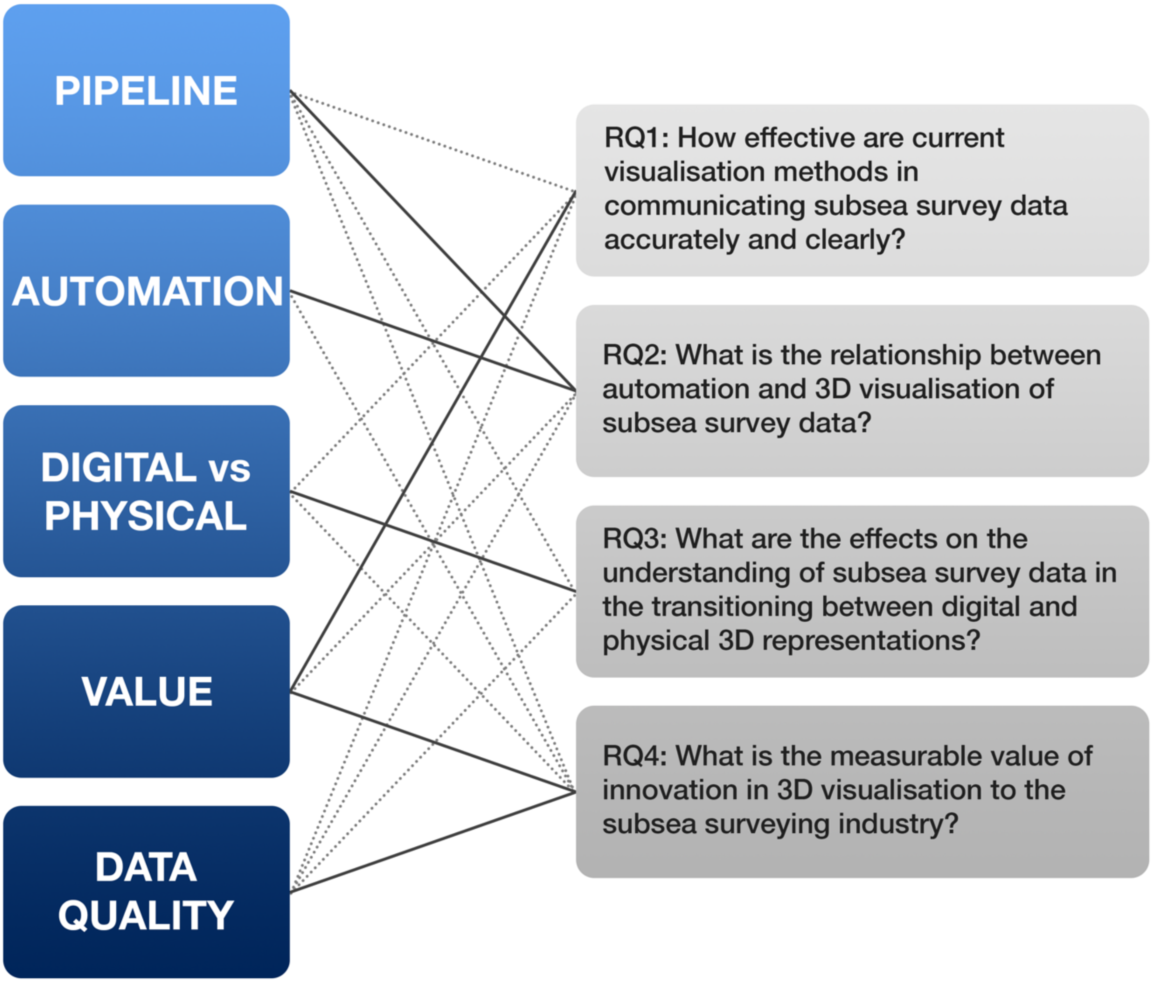

Figure 3.2: Diagram mapping the relationships between research themes and research questions

4 Background

This chapter will introduce the knowledge required in approaching the successful visualisation of subsea survey data – how data is gathered, a typical commercial visualisation process, and a look at the most relevant emerging visualisation methods.

4.1 Visual communication

For thousands of years, images have been used as a means of communication, giving us new ways of telling stories, illustrating concepts and ideas, presenting information, and explaining statistics (Dragicevic and Jansen, 2012; Friendly and Denis, 2001).

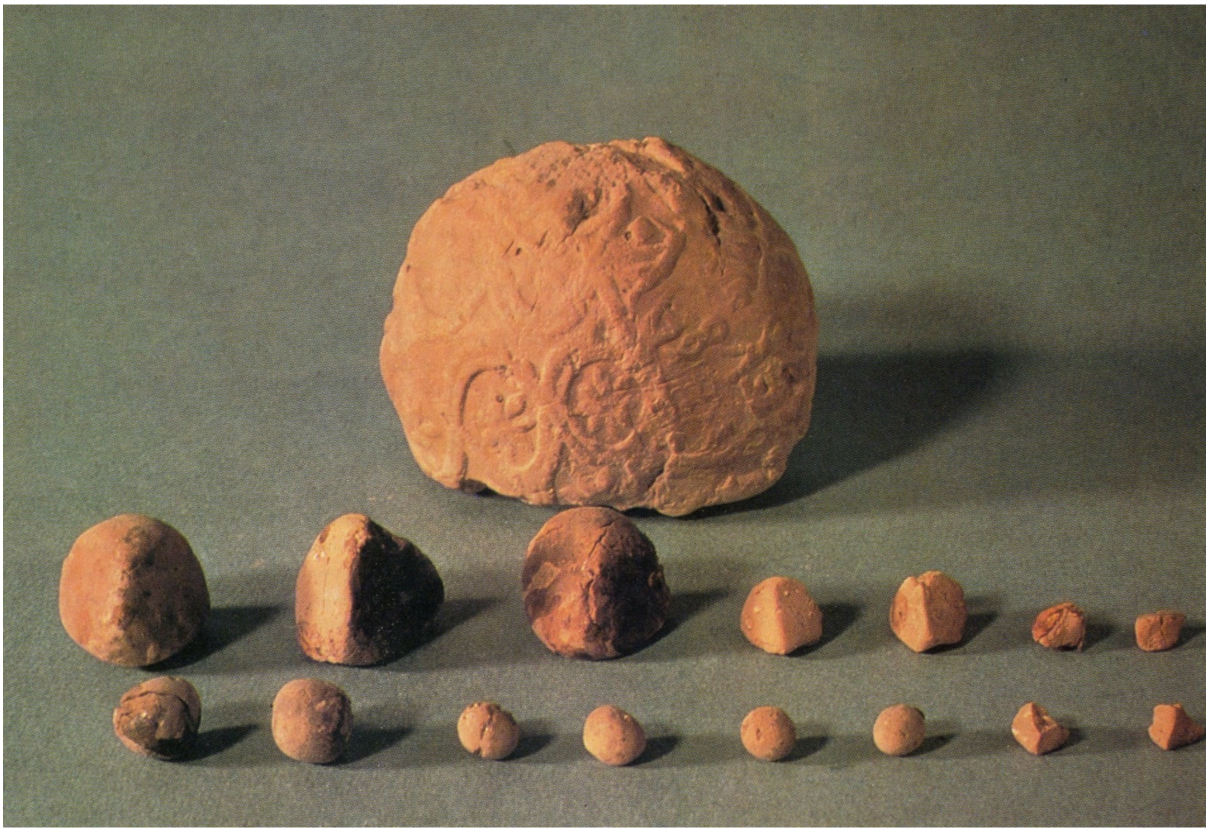

Figure 4.1: Mesopotamian Clay Tokens, circa 5500 BC, were believed to have been used to externalise information and support visual thinking before paper and writing were invented (Dragicevic and Jansen, 2012)

In his ground-breaking and critically important book, *The Visual Display of Quantitative Information*, Tufte explored new approaches to designing statistical graphics, showing us ways in which "graphics reveal data", believing that "graphics can be more precise and revealing than conventional statistical computations" (Tufte, 2001). Although written more than a decade ago, his structured approach to communicating statistical information visually is still considered one of the most relevant texts of today.

By communicating ideas and data visually, we can open up new ways of seeing information. Few (2013) states that "one of the great strengths of data visualization is our ability to process visual information much more rapidly than verbal information." This is because our visual perception and processing of images is handled by the visual cortex in the rear of the brain, and is much faster than thinking, which is handled by the cerebral cortex in the front of the brain (Few, 2012; Kirk, 2012). It enables the viewer to quickly understand what they are looking at, form conclusions and find patterns that may not have been obvious, or even noticeable, previously.

Similarly, combining the use of images to convey information with the high levels of technology readily available today opens up an almost unlimited number of new approaches and possibilities. We are now able to create, store and process vast quantities of data quicker than ever before. Kirk (2012) tells us of the exponential growth in digital information being generated – "in the last two years alone [2010-2012], humanity has created more data than had ever previously been amassed." Despite incredible advances in visualising and presenting information, we are now creating and generating information faster than we can find a suitable use for it. This suggests that new ways of managing this information need to be developed – this could involve simplifying the datasets, increasing processing power to handle larger volumes of data, streamlining the presentation process or even just showing greater amounts of data in a more efficient manner.

Current practitioners have opted for a combination of these approaches, although there is a particular focus on exploring how we view and interact with data. In an included commentary on an article by Few (2013), Robert Kosara wrote that "while static charts and visualizations are undoubtedly useful, they make little use of the immense computing power that is readily available to us today", and goes on to say that "interaction in visualization enables the fast exploration and discovery of data patterns that the user may not even have expected." This view is typical of data visualisation as a developing field – there is often too much data to simplify or streamline, and so there is a clear focus on developing better and faster ways of communicating data, whether this is through the addition of interactivity or perhaps the use of different types of media.

However, developments in both visualisation and technology are not without their disadvantages. In what could certainly be considered a "golden age of data visualisation" (Klein, 2013), we are faced with so many options and approaches that it has also encouraged a wide variety of less-than-useful imagery to be created, enveloping us in a growing burden of confusion and inconsistency. Few (2013) explores this trend, saying that "since the turn of the 21st century, data visualization has been popularized, too often in tragically ineffective ways as it has reached the masses through commercial software products". This comment refers to the increasing availability of software, such as PowerPoint or Prezi, which is often seen as a means for quickly creating visual presentations with little or no technical or design skill.

This increase in ineffective methods of communicating data is likely to only be temporary, however; like any new topic, as new research is undertaken and skills are developed, the general understanding of and approach to data visualisation will improve. The exploration of better ways of presenting data, or developing new methods of interacting with information will also work towards an increased understanding in both current and future practitioners.

4.2 Information versus data

The terms 'information' and 'data' are commonly used interchangeably, but refer to different things. In defining these terms, McCandless (2010) experimented with a familiar approach linking data, information, knowledge and wisdom – representing it visually and calling it a "Hierarchy of Visual Understanding", shown in Figure 4.2.

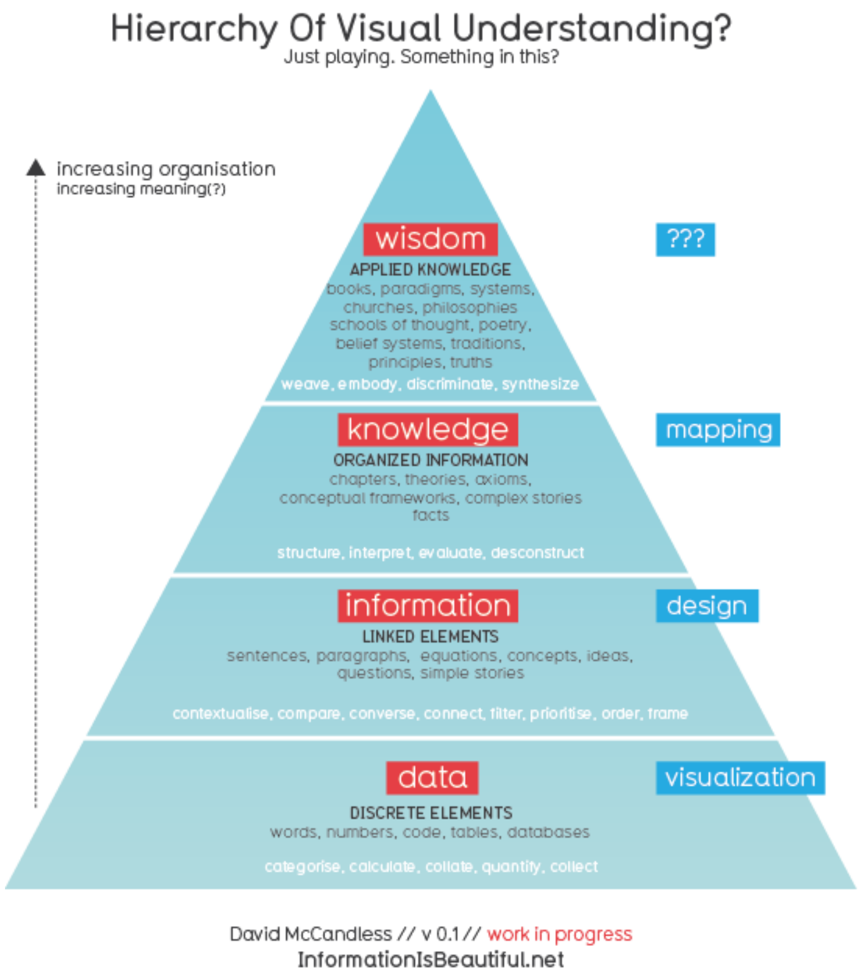

Figure 4.2: Hierarchy of Visual Understanding (McCandless, 2010)

Data (from the singular *datum*) are typically raw, unorganised numbers or facts, and need to be organised, processed and presented to have any meaning. **Information** is the result of interpreting and structuring raw data, creating new understanding where previously there may have been none, or something that has already been given meaning, although it's possible that it could still be an interpretation to some extent. The use of information can lead to new **knowledge**, through the application of experience and decision-making, which if successful, leads to **wisdom**.

For example, multi-beam sonar systems generate a series of raw, numerical outputs – **data** – that seem meaningless at first glance. On further inspection, these are actually a series of three-dimensional coordinates that can be used to construct a virtual model of the scans, providing new information on how the underwater object or location looks in three dimensions. This **information** allows a viewer to examine particular aspects of the original data, perhaps finding damaged sections of a building, or items that were previously missing and needed to be located. Through the application of experience and decision-making, this generates new **knowledge** of any potential issues. In this example, **wisdom** is achieved by recognising and resolving the problems identified using the data and information, and working to avoid them again in the future.

Understanding the difference between data and information is crucial in defining different types of visualisation. Visualisation can allow non-specialists to understand complex ideas and outputs, and makes both information and data far more accessible than ever before. Although 'data visualisation' is often considered to be a smaller subset of the broader term 'information visualisation', it is no less important, and provides us with new and interesting ways of translating the abstract into something more understandable, using a mixture of constantly developing visual tools and methods.

4.3 Visualising data

Keim et al. (2006) define **information visualisation** as "the communication of abstract data … through the use of interactive visual interfaces". Williams (2011) quoted Benjamin Wiederkehr (of Datavisualization.ch), describing information visualisation as "visual representations of information, data or knowledge often used to support information, strengthen it and present it within a sensitive context". Both of these practitioners maintain that information already has at least some meaning, and information visualisation carefully considers the best way to present it.

In contrast, **data visualisation** is typically described as the representation of data (often numerical) using visual methods, and is generally created from raw, unprocessed and uninterpreted source material. More specifically, Tufte (2001) describes the results of using these visual methods as data graphics, which show "measured quantities by means of the combined use of points, lines, a coordinate system, numbers, symbols, words, shading, and color". It is important to note that although data visualisation has a focus on improving the presentation of data, it is also about extracting meaning, which should not be at the expense of the accuracy and truth of the underlying data source being visualised.

The goal of data visualisation varies across disciplines, such as helping analysts compare different sets of population data, providing statisticians with a new way of finding patterns in numerical data by viewing it in different ways, or mapping social media posts to identify current trends. The use of 3D visualisation opens this up further, and sees regular application in fields such as medicine, mathematics and archaeology.

Data visualisation can also be used not only to improve the presentation of data, but to improve human cognition of data, allowing for better understanding of the underlying data and creating new opportunities to recognise patterns and trends, which might not be easily accessible in a 'raw' or unprocessed format. Ware (2000) states that if presented well, "one of the greatest benefits of data visualization is the sheer quantity of information that can be rapidly interpreted" – as this then relies on visual perception and the speed and efficiency of our visual functions, which are much faster at understanding visualisation than our slower cognitive processes.

In its simplest form, Few (2013) describes data visualisation as having two main purposes – "sense-making … and communication". This notion of improving communication is reinforced by Kosara (2008), who states that "data must come from something that is abstract or at least not immediately visible", and requires some degree of transformation to enable a clearer explanation of the underlying content.

Tufte (2001) believes that "graphics reveal data" while Friedman (2007) develops this idea further, telling us that "to convey a message to your readers effectively, sometimes you need more than just a simple pie chart of your results". Current visualisation practitioners continue to share this viewpoint and are working to develop innovative new ways of presenting data, believing that the communication of complex data can be improved by using new visual methods, which also allow for a greater amount of information to be understood more efficiently (Few, 2012; Kirk, 2012).

4.4 Collecting subsea data

SOund **N**avigation **A**nd **R**anging (or SONAR) is a type of acoustical imaging used to gather information about objects and locations underwater. Sonar can be used to "develop nautical charts, locate underwater hazards to navigation, search for and map objects on the sea floor such as shipwrecks, and map the sea floor itself" (NOAA, 2014).

There are two types of sonar technology – active and passive. Active sonar uses both a transmitter and a receiver, and sends out a series of sound pulses, or 'pings', and records the echoed signals – that is, signals that have bounced off of objects in their path. In contrast, passive sonar does not emit any sound pulses, and is instead used to 'listen' for sounds being emitted from other sources, perhaps from other ships or marine animals. Passive sonar finds limitation in being unable to "measure the range of an object unless it is used in conjunction with other passive listening devices" (NOAA, 2014).

There are several types of sonar system available, although the most commonly used are multi-beam echo sounders or side-scan sonar. Multi-beam echo sounders (or MBES) create a wider 'swath' of soundings to cover a larger survey footprint than a single echo sounder (as shown in Figure 4.3). This allows a broader area to be covered in a shorter amount of time. Multi-beam sonar surveys generate bathymetric data using a Cartesian coordinate system (typically X, Y, and Z, where Z is vertical depth). This data can be viewed as a series of points in space, creating a three-dimensional 'point cloud', which can be moved, rotated, explored and measured.

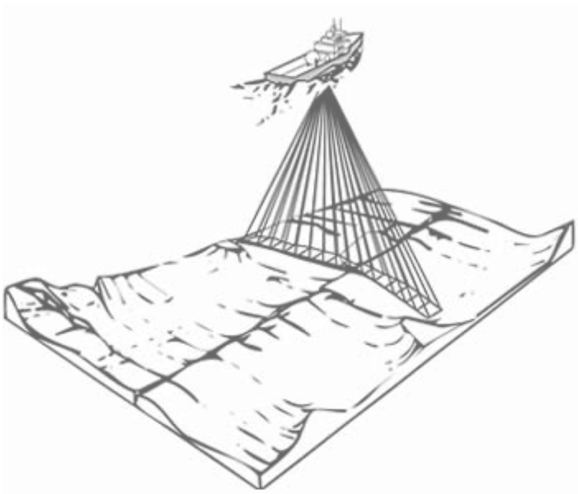

Figure 4.3: Example swath generated by a MBES or multi-beam echo sounder (Oceanic Imaging Consultants, no date)

Side-scan sonar is commonly used for detecting objects on the seabed, although "most side scan systems cannot provide depth information" and are likely to be used in conjunction with a multi-beam echo sounder (NOAA, 2014). A side-scan sonar system can be hull-mounted or towed (as seen in Figure 4.4). Similar to a multi-beam echo sounder, side-scan sonar will emit a wide swath of soundings, but will output a two-dimensional image of the seabed rather than a three-dimensional point cloud. This can be used to locate and identify objects, as any objects such as wreckage, rocks or debris will create a stronger signal return, leaving contrasting shadows behind raised areas – highlighting items that may be of interest.

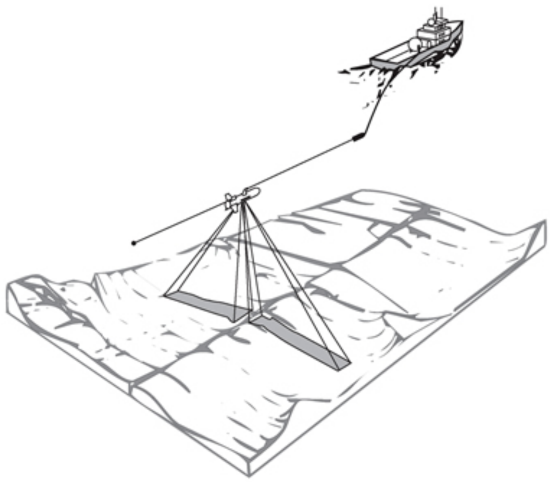

Figure 4.4: Example of a towed side-scan sonar system (Oceanic Imaging Consultants, no date)

For the purposes of this research, focus will be on the use of three-dimensional data generated through the use of multi-beam sonar systems, which are already extensively used by the industry partner, ADUS DeepOcean. Side-scan sonar is not relevant within the scope of this research, as it does not provide three-dimensional point cloud information, and forms part of a different working process entirely, being better suited to providing seabed imagery rather than creating subsea models.

Laser systems can also be used to collect subsea survey data, although this is a much more recent innovation. Similar to multi-beam sonar, laser data allows for the capture of objects and locations as three-dimensional point clouds, and as ADUS DeepOcean are planning to invest in laser scanning equipment, this will likely become more relevant in future case studies as this research is developed further and laser data becomes available for visualisation. It is important to note that although there are differences between laser and sonar data (in particular, the resulting data quality), there are a great number of similarities in how both types of data are processed and visualised – the case studies are intended to present knowledge which can be applied beyond the use of only multibeam sonar data.

4.5 Visualising subsea survey data

> "Through visualization, we are seeking to portray data in ways that allow us to see it in a new light, to visually observe patterns, exceptions, and the possible stories that sit behind its raw state. This is about considering visualization as a tool for discovery." (Kirk, 2012)

Through critical reflection undertaken during the author's own creative and commercial practice, the current industry workflow can be simplified and summarised in three core stages: acquisition, processing, and visualisation (shown in Figure 4.5). Table 4.1 provides further information on the typical tasks undertaken during each of these three core stages.

Figure 4.5: Summary of current industry workflow

ACQUISITION	Planning (e.g. team/resource management, sailing lines and coverage) Mobilisation Calibration (reducing margin of error – factoring equipment offsets, GPS, sound velocity, attitude/heading/heave/position/velocity) Development (testing new equipment as part of established workflows) Surveying
PROCESSING	Post-processing (applying further survey corrections if required) Project organisation (e.g. recording offsets, file naming/consistency, data sharing) Editing (including trimming, cropping, gridding, subsampling) Cleaning (such as removing data noise or abnormal points) Segmentation (separating seabed/monopile/scour/cables/etc.)
VISUALISATION	Data selection (ensuring site coverage, avoiding duplication or presentation of unnecessary data) Visual experimentation (including applying colour)

	Creating occlusion objects (Rowland, 2010)
	Surface modeling
	Creating deliverables (preparing WreckSight files, 3D printing, etc.)
	Data evaluation and analysis

Table 4.1: Examples of tasks undertaken during acquisition, processing and visualisation of subsea survey data

The author's experience in undertaking these core stages has been informed and developed by the opportunity to work on live commercial projects with the industry partner, ADUS DeepOcean. As a result, the author has focused on detailing their internal workflow and processes, which are regularly used in the acquisition of high-resolution survey data. These same processes can also be used to acquire standard-resolution survey data, adopting a more flexible approach to defining quality criteria. The following sub-sections describe the practical application of each of these three core stages in visualising subsea survey data.

4.5.1 Acquisition

Acquisition involves the collection or generation of subsea survey data. This is a complex and technical process, usually undertaken by hydrographic surveyors, and requires the combination of a wide variety of equipment and software. The following sections detail this process as undertaken by ADUS DeepOcean.

To begin acquisition, a suitable vessel must be available, and the equipment must then be 'mobilised' (Figure 4.6). This typically involves the use of ADUS DeepOcean's own Independent Sonar Head Attitude and Positioning System (or ISHAPS). This provides a means of aligning all of the equipment vertically using known and/or measurable offsets to increase survey accuracy, that "dramatically helps to improve the quality of the data" being gathered (Dean et al., 2010). Once prepared, the ISHAPS can be attached to the vessel (Figure 4.7), so that surveying can begin.

Figure 4.6: Survey equipment ready to be mobilised

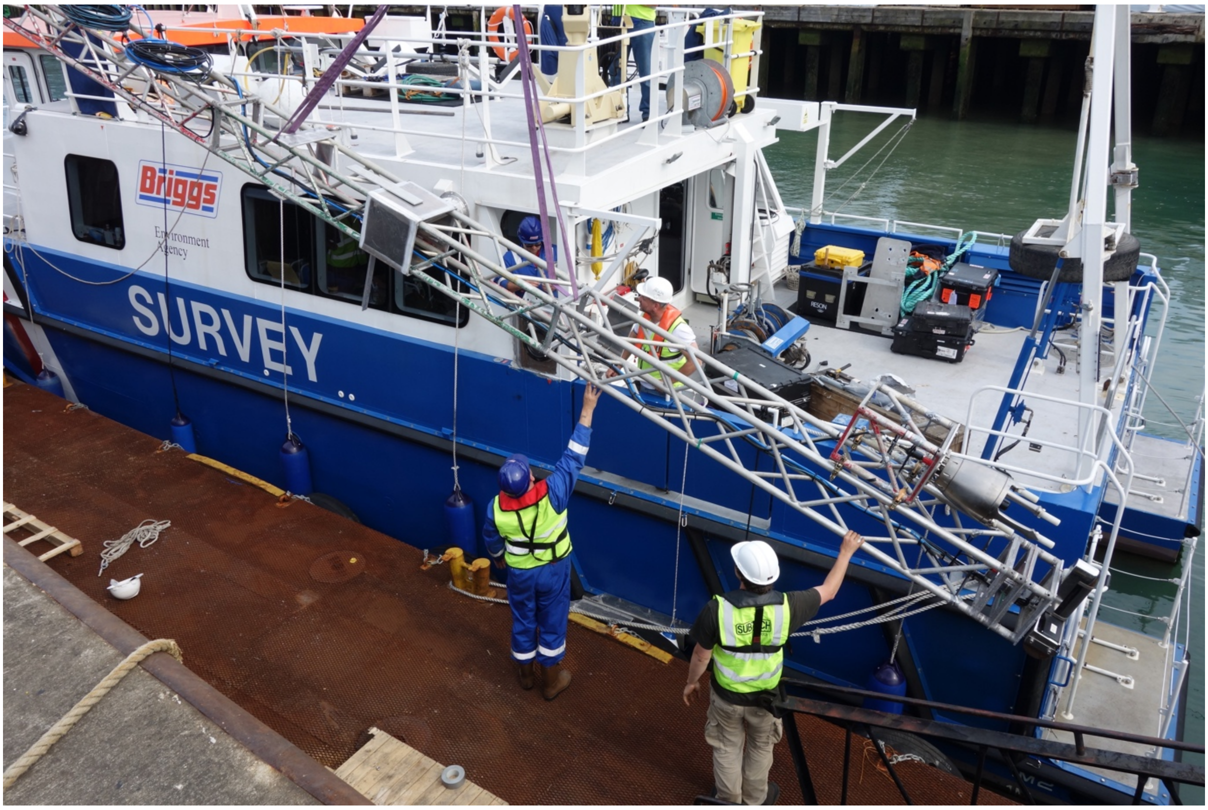

Figure 4.7: ISHAPS being deployed on the side of a survey vessel

A number of devices can be mounted on the ISHAPS, depending upon the type of survey being completed. This usually includes a multi-beam echo sounder (normally mounted on the bottom of the ISHAPS, shown in Figure 4.8, and an inertial navigation system, consisting of both RTK (Real-Time Kinematic) GPS and a motion reference unit. ADUS DeepOcean "has found that the best high frequency multi-beam systems give the best results – provided they are coupled to the best motion reference units and positioning systems" (Dean et al., 2010). A sound velocity profiler is also used, enabling correction of the multi-beam echo sounder data by measuring differences in the speed of sound at varying water depths. All of the survey data is commonly collected and recorded using QPS QINSy – a suite of software applications designed specifically for gathering and managing survey data.

Figure 4.8: Reson 7125 multi-beam sonar fixed to the bottom of the ISHAPS

Although some processing happens alongside acquisition (such as applying real-time GPS corrections), the bulk of processing happens once acquisition is complete. On larger, more complex jobs with multiple assets, acquisition and processing may run simultaneously, but the acquisition of a single asset will be completed so that processing of this can begin whilst the next set of data is being acquired. This proves to be a more cost and time effective solution, although relies on having a larger team with the appropriate skillsets available.

4.5.2 Processing

Processing the survey data happens in stages and relies on combined expertise with some being carried out by the hydrographic surveyors, and some being carried out by the team who will visualise the results – in this case, those who are both researchers and visual practitioners. As a result, processing could be considered as a bridge or 'handover' between these two areas of expertise.

The first stage of processing is to ensure that GPS corrections have been applied, and if live RTK GPS is not being used, additional software is needed to post-process the survey data, correcting any potential errors in positioning, which ensures the highest level of accuracy. Some correction of this data should already have happened during acquisition – for example, the use of a *POS MV*[2] motion reference unit records and applies "accurate attitude, heading, heave, position, and velocity data" (Applanix, 2013) during the survey, which reduces the amount of post-processing required later.

Once the data has been corrected, it can be exported from QINSy, ready for 'cleaning' in Fledermaus – "the industry leading interactive 4D geospatial processing and

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[2] Hydrographic equipment providing a geo-referencing and motion compensation (six degrees-of-freedom position and orientation) solution.

analysis tool" (QPS, 2014). During this stage, any unwanted or 'bad' data is removed – this could include removing point cloud noise, edge feathering or 'zero' points (effectively 'inside' the sonar device) – all data points which are unnecessary and overcomplicate the resulting dataset. A large proportion of cleaning subsea survey data is still a manual process requiring time, patience, and an expert with skill and experience of working with this type of data.

Once cleaning is complete, datasets are exported using XYZ formats, which are more accessible than the proprietary QPS file formats, ready for visualisation to begin. Open-source software such as CloudCompare is commonly used to view or further clean the datasets at this step.

4.5.3 Visualisation

As the third and final core stage, visualisation consists of several sub-steps and (in the ADUS DeepOcean workflow) is usually completed by a team of visual researchers. Visualising the processed and cleaned data can be undertaken in a variety of ways, depending upon the requirements of the client and the deliverables they have commissioned. Ongoing research into these methods leads to improvements in both the process of visualisation and the effectiveness of these visual outputs.

Since multi-beam sonar systems generate three-dimensional point cloud data, the focus will usually be on visualisation methods that take advantage of all three of these dimensions – X, Y and Z. It should also be noted that some modern subsea visualisations present three-dimensional information in the form of two-dimensional charts, either paper or screen-based – the working processes are the same, although with a different choice of presentation format to finish. However, this presents an on-going issue in the field of visualisation, which is discussed in section 4.6 in greater detail.

Fry (2007) describes the data visualisation process in 7 distinct stages, as can be seen in Figure 4.9, placed alongside the simplified three-stage core process introduced earlier. Although this process describes visualisation in the context of computational information design, the process is applicable across other disciplines, with a similar approach still being adopted by other practitioners (Kirk, 2012; Ware, 2000).

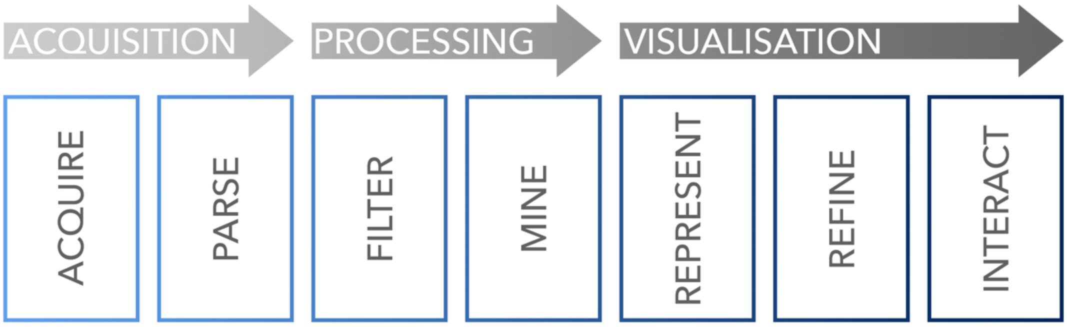

Figure 4.9: Seven stages of data visualisation, adapted from an original diagram by Fry (2007)

In the context of subsea survey data, acquire, parse, and filter refer to the initial acquisition and processing (or preparation) of data, discussed earlier in this section.

Once these first three stages have been completed, the resulting data can be mined for information – an important stage of processing where patterns may emerge, and a narrative can start to be constructed, which helps to identify a way of explaining the data visually. An initial method for representing the data should then be adopted, although this is unlikely to be 'final' at this stage. The intention of prototyping is to get an initial idea of how the data is conveyed, and if this needs to be refined and improved so that the data presentation is clearer, whilst ensuring that the representation of the underlying data is still accurate and true.

Interactivity should also be considered, in particular how an audience will receive this visualisation, and what level of input or control they require to have the best experience possible. Fry (2007) describes the addition of interactivity as "letting the user control or explore the data" and suggests that this could take the form of changing viewpoints or selecting subsets of data. Stating that "adding interactivity to your visualizations is profoundly powerful", Hadley (2018) believes that interactive visualisations improve the overall user experience and should pose and address multiple questions, where users can zoom, focus and freely explore data.

When presenting subsea survey data, interactivity is most likely to involve changing the camera viewpoint, taking measurements, or layering data files (particularly with assets containing multiple sailing lines or passes). There tends to be little or no control over the datasets themselves – for example, when supplying PDF charts where no point cloud data is accessible. In the author's experience, interactive subsea survey visualisations are generally used as a way of 'flying through' a fixed and static dataset in three dimensions (for example, using the proprietary WreckSight software). It is important to note that software such as CloudCompare can be used to not only view datasets but also to edit and process point cloud data. For this reason, point cloud data is typically supplied alongside any other deliverables[3].

Although many subsea visualisation deliverables offer only a basic level of interactivity, subsea visualisation methods are being developed beyond current industry practices towards fully immersive and realistic visualisations (Chapman et al., 2010). However, this approach is far less common in commercial or technical settings where the most frequently used visualisation methods are raw data, processed point clouds and digital surface models[4]. To better understand this, the author further explores and compares the communicative value of both traditional

[3] During the expert interviews, Expert C noted that *raw data* is regularly provided as a client deliverable, though added "this data is never viewed it is just so the client has a copy" (appendix 14.4).

[4] During the expert interviews (appendix 14.4), industry experts identified these visualisation techniques as those which are regularly provided as client deliverables.

and newer methods through a series of workshops (section 7.6) and expert interviews (appendix 14.4).

Finally, it is important to note that data visualisation is an iterative process, and each stage can be repeated or returned to if necessary (similar to design or action research, which are discussed in sections 6.1.4 and 6.1.5 respectively), improving the final output where possible. As an example of this, the left half of Figure 4.10 shows the first method of visualising one particular data-set, and the right half shows the final version of the same dataset that the client received, presented using WreckSight. The WreckSight version[5] provides additional features (such as being able to measure between points) resulting in an entirely different visualisation output, using different preparatory and presentation techniques to communicate the same subsea structure dataset.

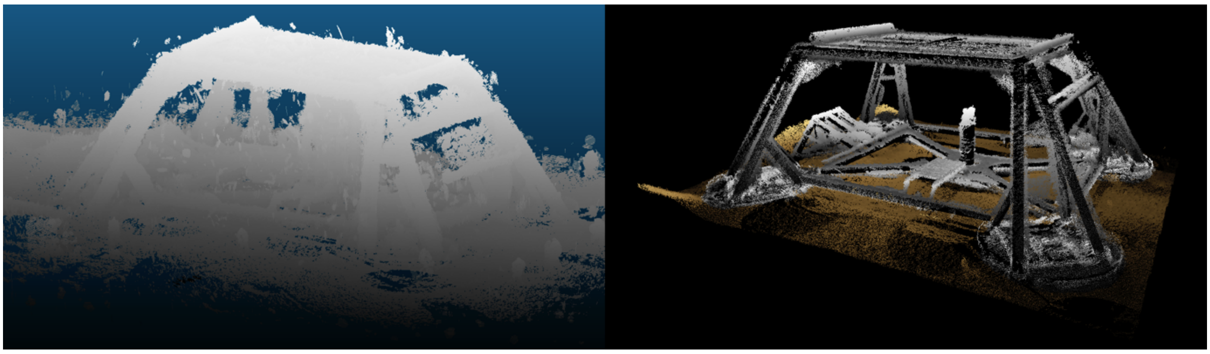

Figure 4.10: Comparison of visualisation iterations (created using the Troll dataset)

4.6 Using emerging technologies

> "For centuries, the profound, central issue in depicting information has been how to represent three or more dimensions of data on the two-dimensional

[5] This version of the data is not provided in the accompanying repository as ADUS DeepOcean was voluntarily liquidated in January 2019, and so access to any proprietary data deliverables is no longer possible.

display surfaces of walls, stone, canvas, paper, and, recently, computer screens." (Tufte, 1997)

Displaying multiple dimensions of information using a method that does not support an equivalent number of dimensions still continues to prove difficult. For example, showing three-dimensional seabed data using two-dimensional charts is often achieved through the use of contour lines or colour mapping, which show changes in depth using lines at defined heights, or a series of pre-selected colours – both of these techniques can be seen in Figure 4.11.

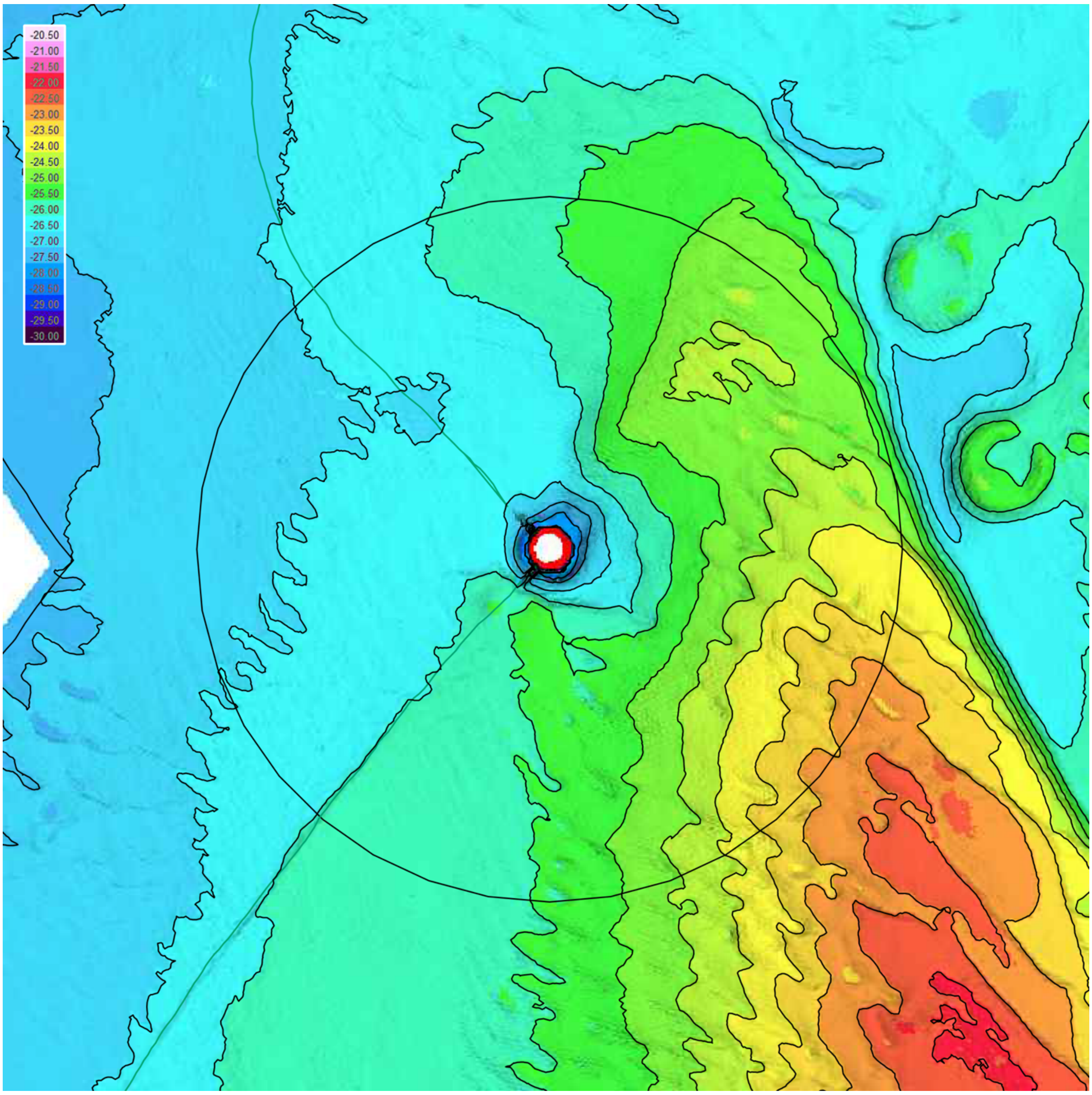

Figure 4.11: Survey image showing contours and colour mapping (image provided by ADUS DeepOcean)

This example introduces two main problems. The first is that presenting three physical dimensions in a two-dimensional 'flat' format does not convey the truest sense of the data. Tufte (2001) states that for graphical excellence, "the number of information-carrying (variable) dimensions should not exceed the number of dimensions in the data". Similarly, if the inverse of this is considered (using the example in Figure 4.11), three dimensions of data are presented using two-dimensional charts – there are not enough spatial dimensions for all of the data being displayed, with the third (Z, or depth) represented using colour. This introduces a second problem, with research showing that the 'rainbow-ramp' approach to colour has proven highly ineffective as the brain cannot naturally order these colours (Borland and Taylor, 2007; Ware, 2000; Rogowitz and Treinish, 1995; Tufte, 1990).

Although there has already been a significant amount of research undertaken on better ways of presenting complex information (Kirk, 2012; Few, 2009; Tufte, 2001; Ware, 2000), there still remains an imposed limitation on what can be practically displayed, and exceeding these limits can cause the underlying data to become cluttered and lose some or all of its meaning. Tufte (1990) even went as far as defining confusion and clutter as "failures of design, not attributes of information".

In response to this, visualisation practice has started to look towards developing entirely new ways of presenting data, such as the use of stereoscopic rendering of 3D computer graphics and animation – the use of two slightly different images to 'fool' our brains into thinking they are looking at something real and three-dimensional. This method presents a different image to each eye, creating the illusion of depth – allowing us to 'see' three dimensions on an otherwise flat screen. There are several different techniques for how the images are presented exclusively to each eye, but one of its simplest forms, called anaglyph stereoscopy, uses colour-tinted glasses to restrict each image to the eye that it is intended for. An example of this can be seen in Figure 4.12, requiring red/cyan anaglyph glasses to view fully.

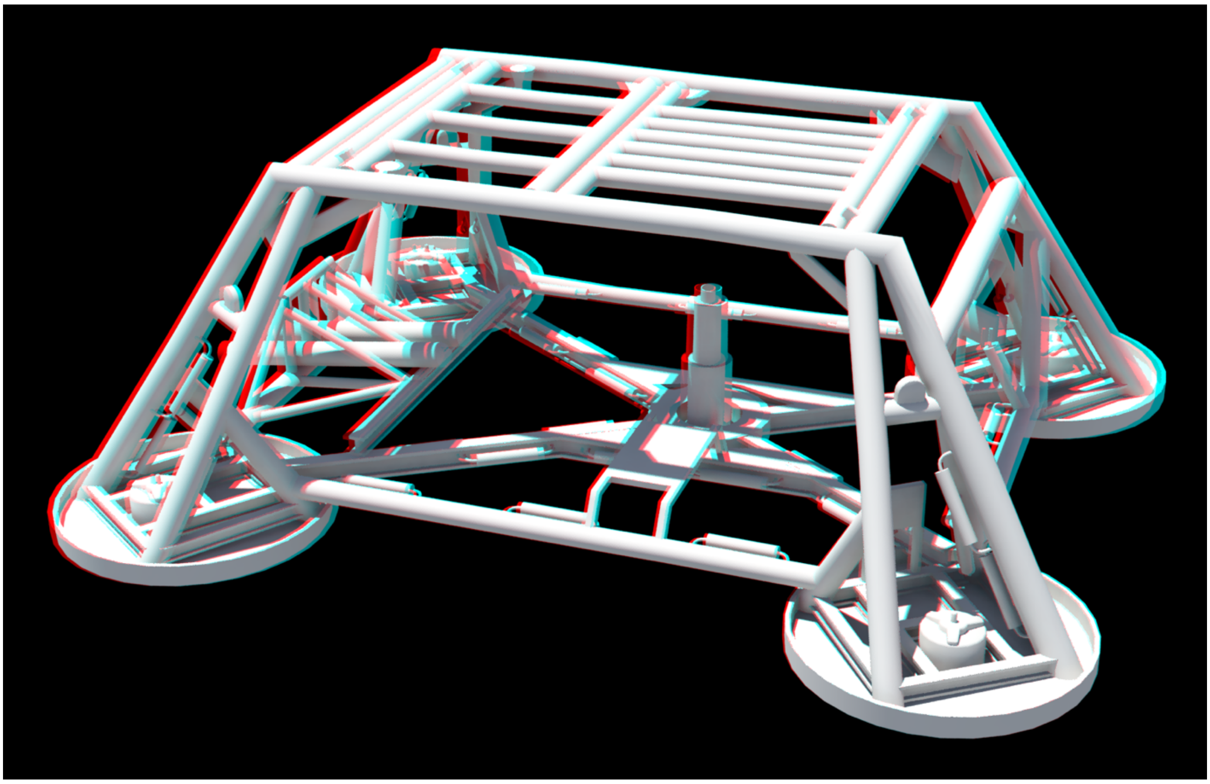

Figure 4.12: 3D render of the Troll dataset, presented using anaglyph stereoscopy

Figure 4.13: Example of a 3D print, created by the author using data gathered during a subsea survey (showing a wind turbine monopile affected by scour)

However, one of the most exciting developments has been the introduction of 3D printing, or rapid prototyping technologies. These allow for the fabrication of three-dimensional physical objects from a digital model, and are typically created using a process called additive manufacturing, where successive layers are printed on top of one another to create the finished object.

An example of a 3D print can be seen in Figure 4.13, which shows an area of seabed (measuring 100x100m) surrounding the base of an offshore wind turbine, based on data gathered using multi-beam sonar. As a particular point of interest, the process of ‘building’ this through adding layers creates a similar effect to the already familiar contour mapping used in survey charts.

By viewing three-dimensional data in three suitable dimensions (maximising the use of information-carrying variables), users can still explore, measure and make decisions, and research suggests that through good visualisation, the understanding of data can be both quickened and increased (Few, 2013; Yau, 2013; Kirk, 2012).

Roberts et al. (2014) also believe that “mapping data to an appropriate visual form is a key to creating useful visualizations”, with more recent developments involving the inclusion of time, interactivity or sound, or making use of these newer technologies such as stereoscopic rendering or 3D printing – that is, beginning to look ‘beyond the screen’.

Although people have been ‘making’ for hundreds of years, the notion of creating tangible data as a visualisation technique is both new and exciting, and there is very little formally published work available (Gwilt et al., 2012), and even less when applied to subsea survey data. David Sweeney, project designer of Microsoft

Research project Physical Charts[6] (Figure 4.14), tells us that by "putting data on screens, it's adding to the visual noise – we're so overloaded with screen-based media", and believes physical visualisations to be the better option (Brewer, 2014). In particular, pie charts have proven to be unpopular as a means of representing data, with Tufte (2001) stating that "pie charts should never be used", and so the Physical Charts project was an attempt at making "data and data visualisations legible to ordinary people in their daily lives" (Microsoft Research, 2014).

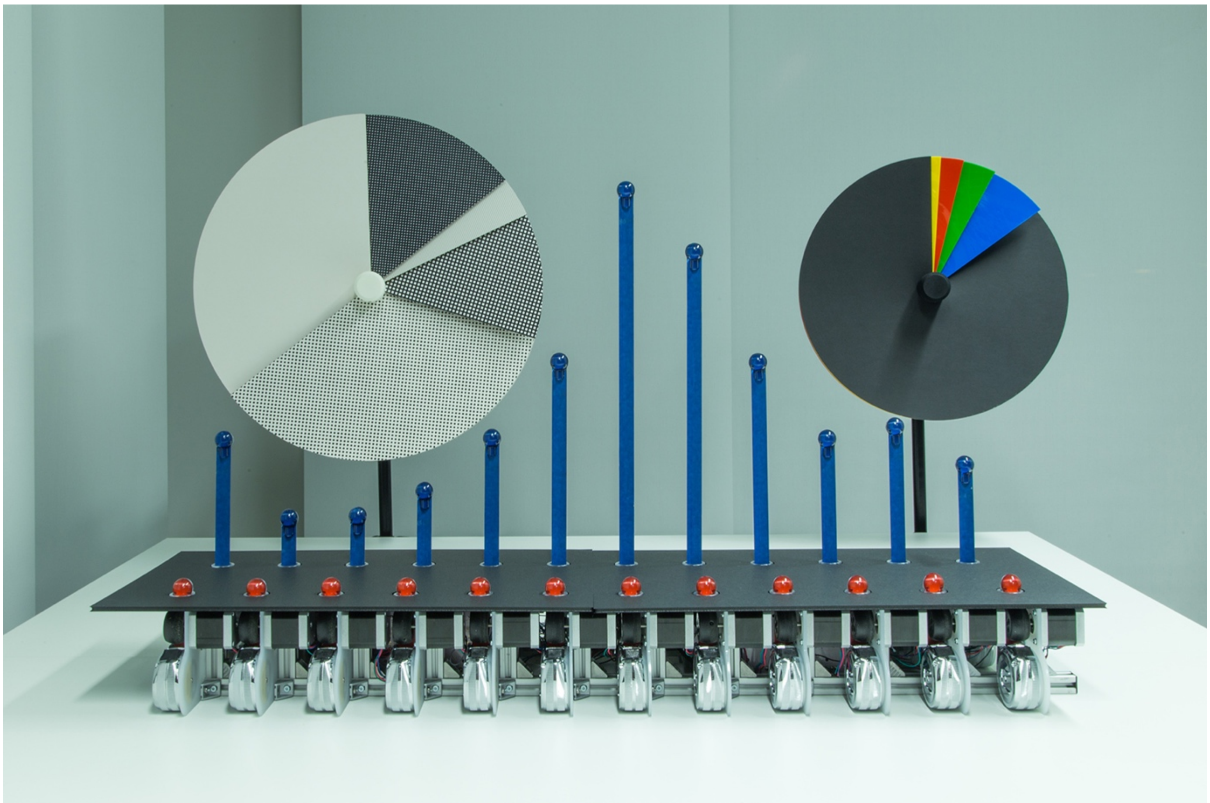

Figure 4.14: Example of data visualisation created as part of the Physical Charts project (Microsoft Research, 2014)

[6] Physical Charts is a Microsoft Research project which aims to simplify the increasing complication of data visualisations by making playful use of long-established formats such as pie charts and bar graphs in a physical and minimalist form.

Believing tangible data to be in its infancy, Gwilt et al. (2012) state that "the creation of a physical object based on a digital data set is in a sense a new 'complex' media form", and conducted a series of pilot studies to explore the creation of data-informed objects and if they could improve cognition of the underlying data. They found that the data-objects easily stimulated discussion, although some were too abstracted from the data to have any easily gained meaning. However, with careful consideration of material, shape, texture and so on, it is believed that data-objects offer an "extended visual language" which can "potentially broaden the community of understanding" (Gwilt et al., 2012).

With the application of tangible data and the physical representation of multiple dimensions, an entirely new range of visualisation solutions now becomes available. Clients can hold a scale model of their subsea structure, explore interesting features, and even identify or measure important or damaged components. If we consider these explorable dimensions, viewing an on-screen visualisation presents all of its elements primarily to a single sense – sight. In contract, viewing a 3D printed visualisation can potentially present the same dataset, but this time taking advantage of two senses – sight, and touch. It is for this reason that tangible data can offer a richer experience without overloading the senses of the viewer. Despite being a relatively new area of research, there still seems to be little understanding as to why physical visualisation methods seem to offer increased engagement with and better understanding of data (Gwilt et al., 2012).

Although 3D printing is not a new innovation, it has been identified through the author's practical work that subsea survey companies have not yet readily adopted this as a useable or mainstream solution – although there is no single clear explanation for this. As such, this topic will form one of the key research themes, and will be developed throughout the future case studies.

5 Contextual Review

This chapter presents the contextual review and each of the contributory parts. As a multi-method approach has been adopted throughout this practice-led research (chapter 6), the contextual review is also addressed by combining methods. This approach is of particular importance in the field of subsea surveying, where "very little research has been published in this field" (Rowland, 2010) and so a multi-method approach allows for the triangulation of knowledge using additional methods.

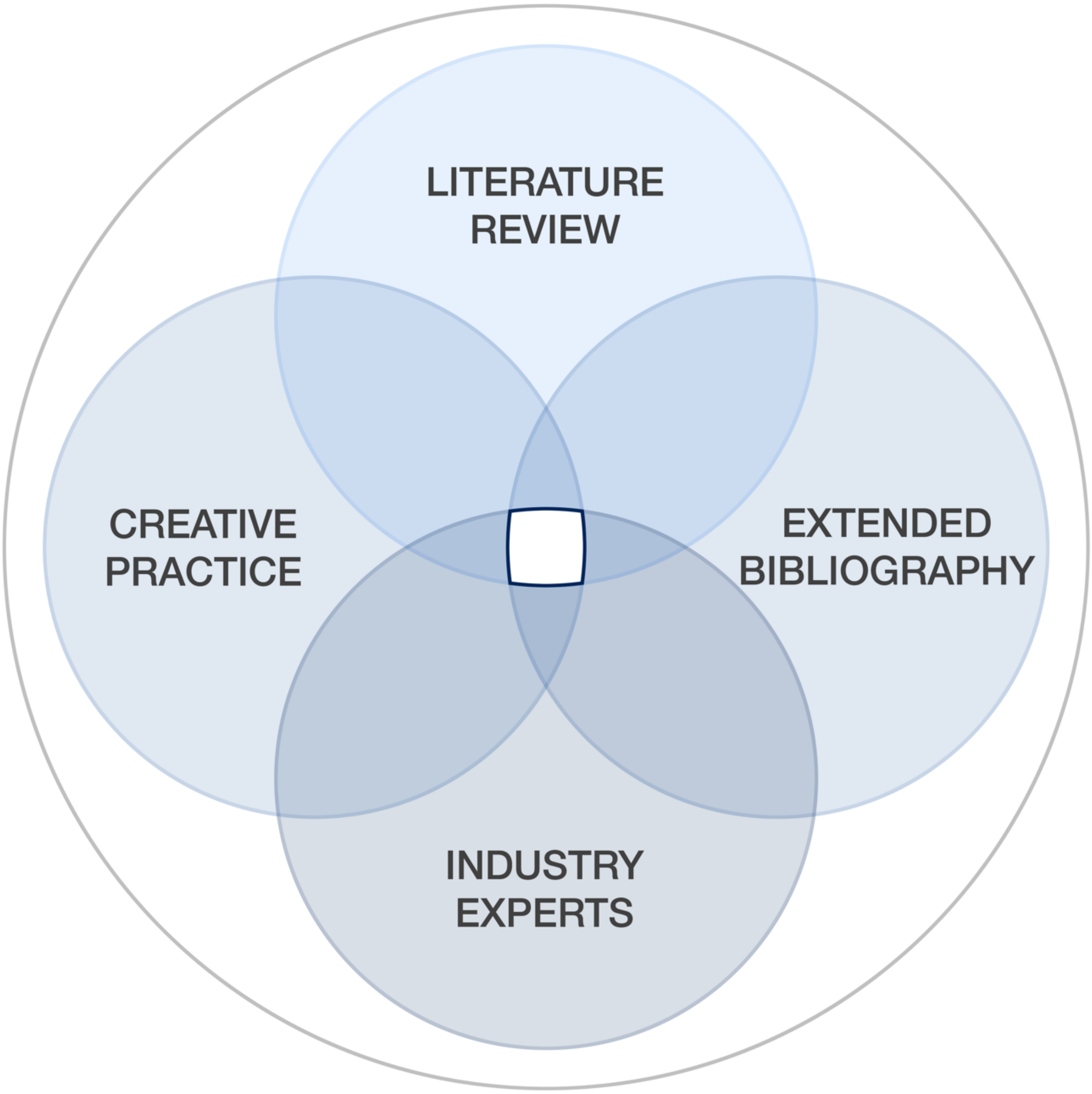

Figure 5.1: Visual mapping of contextual review and component parts

The contextual review is visually represented in Figure 5.1, where each method of contextualisation confirms or denies findings from the others, and ultimately reveals gaps or limitations in knowledge from more than one viewpoint.

Placed on a spectrum from academia to industry, this contextual review includes a traditional literature review compared against the practical views and opinions of the offshore surveying industry. These are then connected by the inclusion of the author's own reflection on creative practice (involvement in commercial projects) and an extended bibliography – broadening the literature review in a further attempt to find and highlight the most relevant and important knowledge.

5.1 Literature review

This section provides a review of the key research literature, and the approach taken in searching for this. The literature review was conducted and repeated multiple times throughout the duration of this research,[7] ensuring that the author's work was informed and up-to-date throughout.

It is important to note that there is a very limited amount of published academic work relevant to the 3D visualisation of subsea survey data. Many of the most relevant results referred to the previous work undertaken by the author, 3DVisLab or ADUS DeepOcean. As a result, this literature review forms part of a broader multi-method contextual review.

5.1.1 Search strategy

[7] Starting in December 2013 and updated until May 2020.

A variety of different sources were used in locating relevant and important literature. This included compiling a list of academic journals and conferences related to this research, and undertaking a series of keyword searches using major academic databases. This was later expanded to include more general searching via additional search engines.

						ACM	IEEE
	Visualisation					1,155	13,493
3D	*Visualisation*					288	1,708
		Sonar				2	4,712
	Visualisation	*Sonar*				0	24
3D	*Visualisation*	*Sonar*				0	5
	Visualisation	*Sonar*	*Stereoscopy*			2	0
	Visualisation	*Sonar*		*(3D) Printing*		0	1
	Visualisation	*Sonar*			*(Data) Grading*	0	0
3D	*Visualisation*	*Sonar*	*Stereoscopy*			2	0
3D	*Visualisation*	*Sonar*		*(3D) Printing*		0	1
3D	*Visualisation*	*Sonar*			*(Data) Grading*	0	0
3D	*Visualisation*		*Stereoscopy*			0	10
3D	*Visualisation*			*(3D) Printing*		0	22
3D	*Visualisation*				*(Data) Grading*	0	7

Table 5.1: Combinations of keywords used throughout the literature review, with total search results from the ACM GraphBib and IEEE Xplore databases

Different combinations of keywords were used throughout the literature search; these are shown in Table 5.1. The rightmost columns show the number of search results for each keyword combination found in the two most relevant databases – ACM GraphBib and IEEE Xplore. The dark shaded row (3D, Visualisation, Sonar) shows the smallest suitable combination of keywords that were used to ensure that results were relevant to this research. Earlier searches were also conducted using fewer keywords (e.g. only *visualisation*) though this proved to be ineffective and offered too many irrelevant results (these are shaded light grey).

This table shows the UK use of *visualisation*, though the US alternative of *visualization* was also used throughout so that potential results were not excluded.

5.1.1.1 Journals

One of the first tasks completed was to locate the most relevant academic journals which could be searched for suitable literature. Those with the most frequently occurring results are shown below:

- Computer Graphics and Applications *(IEEE, 1981 – present)*
- Transactions on Graphics *(ACM, 1982 – present)*
- Transactions on Visualisation and Computer Graphics *(IEEE, 1995 – present)*

In addition to locating these journals, a list of academic publishers was compiled which aided in finding additional journal sources.

Using varying combinations of keywords, as shown in Table 5.1, generally provided a large number of partly-related article results though very few were close to the specific focus of this investigation. Most journals, including two of those specifically listed above, offered no suitable results. Based on their relevance[8] to this research, the following four papers were returned for further review (in chronological order):

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[8] Articles were found to be relevant based on their use of multibeam sonar data for 3D visualisation purposes. There were a significant number of articles using alternative survey data acquisition methods, such as side-scan sonar, and these were excluded as the focus of this research is in working with multi-beam sonar data collaboratively with the industry partner ADUS DeepOcean (section 4.4).

- Chapman, P., Wills, D., Brookes, G. & Stevens, P. 1999. Visualizing underwater environments using multifrequency sonar. *IEEE Computer Graphics and Applications*, 19, 61-65.
- am Ende, B. A. 2001. 3D mapping of underwater caves. *IEEE Computer Graphics and Applications*, 21, 14-20.
- Chapman, P., Bale, K. & Drap, P. 2010. We All Live in a Virtual Submarine. *IEEE Computer Graphics and Applications*, 30, 85-89.
- Bates, C. R., Lawrence, M., Dean, M. & Robertson, P. 2010. Geophysical Methods for Wreck-Site Monitoring: the Rapid Archaeological Site Surveying and Evaluation (RASSE) programme. International Journal of Nautical Archaeology, 40, 404-416.

5.1.1.2 Conferences

Searching beyond academic journals, a list of relevant conferences was also created, highlighting additional resources which could provide access to literature. Many of these conferences were inclusive of both academic and industry practice, offering a broader range of literature results to search within. The most relevant conferences are shown below:

- IEEE VIS *(1990 – present)*
    - *Information Visualization (InfoVis), Scientific Visualization (SciVis), Visual Analytics Science and Technology (VAST)*
- OCEANS *(1970 – present)*
- SIGGRAPH *(1974 – present)*
- Visualization (1990 – 2005)

Similar to searching journals, using conferences to find literature showed a large amount of results though only a very small number that were directly relevant. Two further papers were found for review (in chronological order):

- Dean, M., Lawrence, M. J. & Schwall, D. 2010. A new, accurate shipwreck survey method used during the wreck removal operations of the New Flame. International Tug and Salvage Convention, 2010 Bradford on Avon, UK. ABR Company Limited.
- Campos, R., Garcia, R. & Nicosevici, T. 2011. Surface reconstruction methods for the recovery of 3D models from underwater interest areas. OCEANS '11, 6-9 June 2011 Santander, Spain. 1-10.

5.1.1.3 Databases

Finally, the literature search was expanded to include a number of online databases. This included key resources which overlapped with already-identified journals and conferences, such as ACM GraphBib and IEEE Xplore. This search also included the University of Dundee cross-search catalogue as a significant resource.

As with previous searches, using fewer keywords (such as only *visualisation* and *sonar*) provided a large amount of results. Focussing the search terms narrowed this significantly, typically identifying relevant articles which had already been found previously – only one new paper was included for review:

- Bodus-Olkowska, I. & Wawrzyniak, N. Hydrographic imaging for underwater environment modelling. 18th International Radar Symposium (IRS), 28-30 June 2017. 1-10.

5.1.2 Key literature

Following the literature searching stage, the results were collated and seven papers were found to be highly related to this research. These are reviewed and discussed in the following sections, arranged in chronological order. A distinction is made between *paper author* and *author* for clarity.

5.1.2.1 *Paper 1 – "Visualizing underwater environments using multifrequency sonar" (Chapman et al., 1999)*

Chapman et al. (1999) introduce subsea visualisation through the use of their Seabed Visualization System, used as part of three case studies: modeling a harbour wall, inspecting a sunken military vessel, and visualising underwater pipelines.

In re-constructing the harbour wall using sonar survey data, an automatic process was used to create a series of primitive cube shapes which were positioned as part of the survey data. Rotation of the blocks to match the sonar data was undertaken manually, viewing both point cloud data and 3D modelled blocks simultaneously. The addition of texture, lighting and perspective was intended to "increase the generated model's realism" (Chapman et al., 1999). The purpose of creating such a model is described as two-fold: allowing a user being able to 'fly' around the modelled wall, and recording an 'image' of the harbour which can be surveyed annually and compared to previous years.

Their second case study discusses the Seabed Visualization System as a means of investigating and identifying shipwrecks, providing "a much safer alternative than the hazards of wreck diving" (Chapman et al., 1999). A sonar survey of the SS Richard Montgomery[9] was conducted, as the site contained potentially explosive materials. The resulting dataset is presented as a simple polygonal model, created by 'draping' geometry over point cloud data and coloured using 'rainbow ramp' colours. A second presentation is also provided, where a 3D CAD model of the ship was created and combined with the previously surveyed seabed dataset.

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[9] SS Richard Montgomery was built during World War II, and was wrecked off the Nore sandbank in the Thames Estuary (near Sheerness, England) in 1944 whilst loaded with a cargo of explosive munitions.

Finally, their third case study discusses the acquisition of sonar data as part of a pipeline inspection process. The Seabed Visualization System was used to provide "high-resolution 3D bathymetric computer images" instead of 2D images from side-scan sonar or video footage from an ROV (Chapman et al., 1999). The resulting visualisations offer a view of seabed data augmented with 3D-modeled polygonal pipes that are based on the owner's specifications. The paper authors follow this by noting the scepticism created by moving to entirely computer-generated visualisations as opposed to continuing the use of industry standard reporting techniques such as raw ROV footage or paper-based side-scan sonar outputs.

In their summary, the paper authors state that "by bringing together advanced technologies from both sonar and computer graphics, it facilitates planning and decision making in the oceanographic and off-shore industries" (Chapman et al., 1999).

The work presented in this paper represents a significant development for the visualisation of 3D bathymetric data for a number of reasons. It marks a change in how bathymetric data can be presented, whilst highlighting a resistance from the industry to shift away from the traditional techniques they have become accustomed to. As part of the author's experience working on commercial case studies, a similar resistance was shown to still exist. Although multi-beam sonar is now an integral part of many offshore surveys, there is a continued scepticism in stepping away from the 'tried and tested' techniques used during presentation of this bathymetric data. For example, during the Gabbard case study (chapter 8), high-resolution three-dimensional data was gathered and then presented as two-dimensional PDF charts, with depth mapped using 'rainbow ramp' colours.

This is not always the case however, as other recent projects (including the Troll project presented in chapter 7) relied on the use of WreckSight or 3D prints as deliverables. Though the subsea survey industry has shown a continued resistance to move away from tradition, it is positive to see that this *can* be overcome. Given that the use of *any* bathymetric data was once considered strange or unnecessary, seeing the longer-term results of new techniques is a promising indication for more recent visualisation techniques such as 3D printing, which are still uncommon when working with subsea survey data.

Although this paper marks a significant step forward in presenting multibeam sonar data, there is no discussion of the quality of sonar data. The article considers sonar technology to be "extremely advanced" (Chapman et al., 1999) but makes no mention of the challenges regularly faced, and how to overcome these – such as data being noisy or inaccurate, and the significant processing time often required to even partially address these issues. It is also important to note that whilst some surface modeling was completed automatically by the paper authors (such as the seabed and pipeline objects) the remainder of the 3D modeling was undertaken manually. This is not addressed directly by the paper authors, though is likely as a result of the data quality, object complexity, or some combination of both.[10]

5.1.2.2 Paper 2 – "3D mapping of underwater caves" (am Ende, 2001)

In this paper, am Ende presents a novel method for mapping deep, underground, water-filled caves. This starts with an introduction on how to use divers to gather this type of data and the equipment necessary in making this possible, followed by details of the paper author's approach in tackling this particularly challenging type of data acquisition.

One of the critical elements of the paper author's approach was the use of a digital wall mapper (DWM) – a piece of equipment developed specifically for this project

[10] Informed by the author's practice and commercial placements, addressing poor quality data and high complexity objects continue to be two significant hurdles in automatically creating surface models from sonar data (section 7.5.2).

which used thirty-two sonar transducers spirally arrayed to gather 3D data. Additional equipment was used to supplement the gathered sonar data, and included the use of a motion reference unit as the "distance to the walls was important but not useful unless we knew the DWM's exact position and orientation" (am Ende, 2001).

The paper author moves beyond data acquisition and describes the creation of a bespoke system for viewing data gathered by the DWM. In addition to collecting point cloud data, the mapper's path through the cave system was recorded and stored separately. The sonar data was 'thinned' to form a more even distribution of points, and converted into an XYZ-based file format. am Ende (2001) describes how nearly all of the outlying points in the resulting 3D datasets were removed manually, "where the human eye could recognize false wall points".

The article details some of the challenges faced in mapping a single cave passage using multiple DWM passes. Each pass was compared against its equivalents, and any that were deemed inaccurate were 'forced' to better match the best survey passes by matching distinctive points to the most correct pass; this was described as "the least automatic part of the entire mapping process" (am Ende, 2001).

Finally, the paper author suggests that the next step would be to "mesh the points into polygons to form solid walls", assuming that this could be readily accomplished. However, the paper author quickly follows this, stating that "when it comes to a real, automatically gathered data set ... the meshing isn't so easy" because "the human eye can easily but slowly mesh the points, it's much harder to write a mathematical algorithm that correctly meshes" (am Ende, 2001).

This paper presents a surveying project from start to finish, and discusses some of the most important challenges and how they were addressed. It gives a clear indication of a typical pipeline – through acquisition, processing and visualisation – which is still familiar to those in industry today (as presented in section 4.5). Though modern software and hardware have provided improvements wherever possible, the following challenges are still frequently encountered in offshore surveying projects.

With reference to recording accurate position and orientation data, the paper author describes this as a necessary inclusion, but does not explain its importance or the implications of not having it – providing little justification for survey practitioners to include this in their data acquisition process if they do not already. In the author's experience, capturing accurate positioning data is essential and should form part of accepted good practice – a view also held by ADUS DeepOcean in developing their 74 influencing factors of data acquisition. The author's practice has shown that without positioning data, sonar data typically requires manual registration (positioning and orientation) and this can prove to be a problem when working with multiple overlapping scan segments,[11] requiring a significant additional amount of manual processing to resolve. Manual registration can also have an impact on data integrity and accuracy, and therefore any resulting analysis or measurement is negatively impacted (for example, increasing the margin of error within a dataset).

As part of data processing, the paper author refers to the use of XYZ file formats, and chose to convert datasets to this format. Although there are multiple file formats which can now be used (such as the CloudCompare BIN format), XYZ continues to see regular usage in current offshore surveying projects. This is largely due to its broad compatibility and simplicity – an XYZ file is essentially a text file which contains only point cloud coordinates (one set per line) and no other accompanying data files or metadata. It is easy to transfer and share as a single file with no dependencies, though there is no indication as to the contents or quality of a dataset without having to fully inspect it, unless surveyor notes have been supplied in an accompanying document.

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[11] The difficulties faced when processing datasets without positioning data is discussed further as part of the Gullfaks case study (chapter 9).

Finally, the paper author makes reference to two key challenges: removing noise from datasets and automatically creating surface models. These tasks continue to present a considerable challenge in modern projects. The paper poses no real solution to either of the problems, suggesting that these are best completed manually.

5.1.2.3 Paper 3 – "We All Live in a Virtual Submarine" (Chapman et al., 2010)

Chapman et al. (2010) discuss one of the projects undertaken by the VENUS (Virtual ExploratioN of Underwater Sites) consortium, which was created to aid in making "underwater sites more accessible by generating thorough, exhaustive 3D records for virtual exploration".

This project involved surveying an archaeological site off the coast of Pianosa,[12] with a focus on collecting data for photogrammetric reconstruction. Bathymetric-sonar data played a supporting role alongside hundreds of photographs used to recreate the survey location. A series of 3D models were created to represent the different shapes of *amphorae*[13] which were being examined. This allowed a user to select the most appropriate 3D model and best-fit it to the photogrammetric reconstruction. Being able to record, model and visualise the individual amphorae provided the viewer with a "first-class accurate digital reconstruction of the vessel's cargo as recorded at the time of survey" (Chapman et al., 2010).

Visualising the Pianosa data required the combination of multiple data sources: sonar bathymetry, photogrammetric imaging, and the amphorae database. Bespoke

[12] Pianosa is an island (about 10.25 km^2 (3.96 sq. mi)) in the Tuscan Archipelago in the Tyrrhenian Sea, Italy.

[13] A tall ancient Greek or Roman jar or jug with two handles and a narrow neck.

interactive marine visualisation software was developed, Venus-PD, which was used to "generate an accurate first-person perspective of the entire dive process" (Chapman et al., 2010). This dive expedition is controlled using a standard game controller and includes key events, such as presenting the viewer with wreck history when they arrive at the underwater Pianosa site. Though this project allowed a viewer to experience an accurate archaeological representation, it also refers to a series of best practices and procedures for acquiring and visualising underwater archaeological data. Finally, Chapman et al. (2010) believe there is further value, stating "if the real site is ever destroyed, it's comforting to know that the 3D digital copy will continue to educate and captivate the general public".

The authors of this paper make a number of points which are relevant to modern subsea surveying practice. The most important of these refers to the inherent limitations of sonar data, where colour or texture information is not captured. Though this may not be an essential feature for expert users which are familiar with sonar point cloud data, 'plain' data proved to be a less-effective option for general users. As a result, the paper authors augmented their sonar data with photogrammetry to increase realism, and included the use of additional "special effects" such as "realistic ocean surface rendering" and "underwater biological life" (Chapman et al., 2010). Though the paper authors believe these to be useful in creating an accurate replication of the site, the author's experience and reflection has shown that commercial surveying has little need for these extra features, with surveyors having a preference for simpler datasets. This highlights the importance of knowing the intended audience when visualising data – particularly important in a commercial setting where the addition of unnecessary or unwanted features can increase project costs and duration.

The paper authors also make note of georeferencing both the multibeam and photogrammetric data – it is implied that this should form part of best practice, with the importance of georeferenced data also being noted by am Ende (2001). Despite literature continuing to highlight the importance of recording this, it continues to be an ongoing problem, such as with the Gullfaks case study data (chapter 9) highlighting significant problems when accurate positioning data is not recorded.

As a result of their project, Chapman et al. (2010) propose "a series of best practices and procedures for collecting, storing, and visualizing underwater archaeological data" which are not included in the paper. At the time of writing, the project website containing this information is no longer available, preventing the inclusion of these best practices for discussion, evaluation and further development[14].

5.1.2.4 Paper 4 – "A new, accurate shipwreck survey method used during the wreck removal operations of the New Flame" (Dean et al., 2010)

This paper discusses the use of multibeam sonar in gathering high-resolution survey data of the New Flame, a bulk-carrier cargo ship sunk by collision in the Straits of Gibraltar. Two surveys were completed, approximately six months apart, and the results compared a conventional hydrographic survey to a specialist wreck survey.

Dean et al. (2010) briefly discuss the types of equipment used by ADUS DeepOcean which contribute to gathering the best quality survey, believing that "a competent piece of surveying over a wreck using standard hydrographic survey techniques will rarely provide anything like the same level of information for the salvage team". With a developing awareness of a variety of elements "ADUS [DeepOcean] has identified more than 50 individual factors which impact on multibeam sonar survey quality",

[14] It should be noted that a related VENUS project website and guide was later located, though this was created to "highlight specific issues in the realm of archiving and preservation that are pertinent to marine archaeology" (Austin et al., no date). It does not explore the practical stages of subsea acquisition, processing and visualisation, instead focusing on the preservation of marine data and topics such as metadata and paradata.

stating that the use of multibeam sonar offers true metrical data, something which "forward-looking, rotary and side-scan sonar systems can rarely do, or not with the same level of accuracy or precision" (Dean et al., 2010).

The visualisation of the New Flame data was produced using ADUS DeepOcean's WreckSight software. This offered a three-dimensional and interactive means of exploring the survey data, making it "easier to understand and interpret the data" and providing "clear, understandable information to both the wreck specialist and the non-expert" (Dean et al., 2010). This 'complete picture' proved to be advantageous, as divers were not able to record the same type of information and could only offer a limited view of the survey site safely. The resulting multibeam dataset was used to inform the wreck salvage operations.

Describing multibeam surveys as "more expensive than conventional hydrographic surveys", Dean et al. (2010) believe that the amount of useful information provided is generally worth more than the cost difference to companies, and that high-resolution surveys "should be an essential part of a salvage team's toolkit in the future".

The surveying work undertaken in this paper presents several key points, and it is important to note that the paper authors are informed by both academic and commercial backgrounds. Though previous work has augmented multibeam sonar data to address any limitations in clarity (Chapman et al., 2010), the paper authors instead believe that changes can be made in the acquisition of multibeam sonar data, resulting in high resolution survey data which offers new purpose through an increased level of detail. The paper authors present the means of capturing this higher-quality data, and describe it as a "revelation to those in the salvage industry" (Dean et al., 2010). Their specialist approach was later further developed to address a total of 74 factors during the acquisition of multibeam sonar data (ADUS DeepOcean, 2016), informing the data acquisition used as the basis of the Gabbard case study work undertaken by the author (chapter 8). It should be noted that the author's practice encountered fewer problems[15] when using the data acquired using specialist survey techniques described in this paper by Dean et al. (2010).

Though the paper gives an overview of the working process, the full list of identified factors affecting data acquisition forms part of in-house best practice, allowing ADUS DeepOcean to offer clients a unique approach to data acquisition. It is expected that other offshore surveying companies will likely have some amount of similar in-house best practice processes,[16] though these have not been made available for comparison or analysis in a commercially competitive environment, and there are no published papers which discuss these openly.

A consideration of value is also introduced by the paper authors, where a higher quality dataset can "be equivalent to removing a blindfold from a salvor's[17] eyes" (Dean et al., 2010). Despite specialist surveys being a more expensive option, they offer a viable alternative when considering the overall quality and communicative value of a resulting dataset (further explored using the Troll data and workshops in chapter 7). As a result, it is important to consider specialist surveys as another option rather than the only solution, as not every surveying project will find use for high resolution datasets.

In developing these options further, an awareness of data quality and value *prior to* acquiring and processing survey data can open up new visualisation outcomes. For example, low-resolution or inaccurate data (perhaps captured with limitations on budget or expertise) may not be suitable for digital surface modelling or 3D printing,

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[15] The Gabbard datasets were georeferenced, high-resolution and low-noise, and provided complete coverage of all surveyed assets.

[16] The idea of each companies having their own in-house best practices was also suggested by *Expert B* in the expert interviews study (appendix 14.4).

[17] A person who salvages or helps to salvage a ship, cargo, etc.

and where a client requests these deliverables a means of acquiring suitable bathymetric datasets enabling these types of visualisation should be offered.

5.1.2.5 *Paper 5 – "Geophysical Methods for Wreck-Site Monitoring: the Rapid Archaeological Site Surveying and Evaluation programme" (Bates et al., 2010)*

In this paper Bates et al. (2010) discuss the potential of different subsea surveying techniques for gathering high-resolution data, with tests being completed on two different projects – on an artificial test-site in Plymouth Sound and over the wreck of the *Stirling Castle*.[18]

In their introduction, different sonar techniques are compared. Single-beam sonar is described as being of limited use, where it is only helpful in identifying the largest of archaeological features. Consequently, sidescan sonar provided the "geophysical method of choice for wreck-site exploration and mapping" (Bates et al., 2010). However, the authors go on to describe the problems experienced whilst using sidescan sonar, such as poor positional data, varying resolution and scans being blurred with noise. Multibeam sonar is presented as a solution to many of the identified problems by offering high-resolution 3D data, with improvements in cost and availability making this a standard option on many survey vessels.

Phase I of their project was completed at a test site in Plymouth Sound. A series of artefacts of varying size and material were prepared and deployed upon an area of seafloor. These objects were surveyed using multiple devices: two sidescan sonar, one multibeam sonar and a bathymetric sidescan sonar. Bates et al. (2010) found that recognising all of the artefacts in the resulting datasets proved challenging, though

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[18] HMS Stirling Castle was a 70-gun ship built at Deptford in 1679, for the English Royal Navy. She was wrecked on the Goodwin Sands off Deal on November 27th, 1703.

did find that the "higher the density of good-quality data, the better the definition". A number of contributory survey factors were recorded in an attempt to improve future surveying using both multibeam and sidescan sonar devices.

Phase II of the project took place on the Goodwin Sands, and involved surveying the Stirling Castle wreck. This site was chosen because a "considerable body of geophysical work and diver observations was available to inform the research" (Bates et al., 2010). Using the knowledge gained during Phase I, the wreck was surveyed using an alternative multibeam deployment, where the sonar head was mounted on an 8m deep platform, where it would be positioned closer to the wreck. The resulting multibeam survey data was used to examine the surrounding sandbanks for evidence of shift or change.

Finally, the authors state that:

> "despite the mobilisation costs, when correctly used, multibeam sonar offers curators and archaeologists a cost-effective and rapid technique for undertaking wide-area surveys at a resolution that is also effective for recording distinct site details" (Bates et al., 2010).

This statement reinforces ideas previously introduced (Dean et al., 2010; Chapman et al., 2010; Chapman et al., 1999) where multibeam sonar can offer improvements on safety, speed and cost (particularly when compared to inspections completed by divers), though this has to be carefully balanced against factors such as resolution and accuracy.

With a focus on improving data resolution and accuracy, the paper does refer to the use of additional equipment and corrections which are used to ensure multibeam bathymetric data is as accurate as possible (such as the use of a POS-MV device or GPS base). This is consistent with views found in other literature (Dean et al., 2010) and shares similarities with the ADUS DeepOcean workflow (presented in section 4.5).

However, the paper authors remain focussed on the equipment used during data acquisition, making no mention of other critical factors in the process identified during the author's practice, such as better defining data quality (to evaluate and compare datasets fairly) or understanding the importance of the final visualisation format and how this can be affected by prior data acquisition and processing.

5.1.2.6 Paper 6 – "Surface reconstruction methods for the recovery of 3D models from underwater interest areas" (Campos et al., 2011)

This paper discusses reconstruction of a solid digital surface from point cloud data. The authors believe that point cloud data "lacks connectivity information, and a surface that describes the underlying object is needed ... to achieve its correct visualization" (Campos et al., 2011).

The introduction briefly describes meshing methods at their most basic level describing them as "generic enough to deal with any kind of 3D point clouds provided, that they present some properties". However, this was developed further stating that point clouds obtained through underwater imaging "may not fulfil these properties, which will cause difficulties in the surface reconstruction process" (Campos et al., 2011).

As part of their testing and evaluation, the authors apply a series of recent surface reconstruction techniques. Two of the main problems throughout each of the methods are that point cloud data is typically non-uniform in its distribution, and that point clouds often contain outliers which cause surfaces to be wrongly estimated. Without accurate surface normals, reconstruction results are often poor. In comparing sparse and dense datasets, the authors found that "most of the algorithms offer better results" when processing denser data, and conclude that "good sampling density is a critical requirement to get a correct reconstruction" (Campos et al., 2011).

These findings are important because the paper authors explore and present the success and limitations of sonar data in achieving a data quality suitable for surface reconstruction. Using hydrographic data, which is often noisy or sparse (low-resolution), automatic surfacing has proven to be a challenge and the resulting approach has generally been to create a surface model manually (Campos et al., 2011; am Ende, 2001; Chapman et al., 1999).

Whilst this still often holds true for multibeam sonar data, the paper authors make no distinction between sonar data which is standard, and that which is captured using specialist techniques (Dean et al., 2010). In exploring this further, the author's practice and commercial experience has shown that with high-resolution data some surfacing can be completed automatically. With sufficient data quality, simple objects (such as seabed) can be reconstructed using automatic surfacing methods. However, this is an unpredictable process and useful surfacing results can often be impossible where data quality is reduced or inconsistent (Campos et al., 2011), or where survey objects are complex (section 7.5.2 presents a practical example of this).

5.1.2.7 Paper 7 – "Hydrographic imaging for underwater environment modelling" (Bodus-Olkowska and Wawrzyniak, 2017)

Bodus-Olkowska and Wawrzyniak (2017) present their research on visually integrating three types of hydrographic survey data: multibeam sonar bathymetry, sonar mosaics (sidescan sonar) and contour maps of magnetic anomaly.

Each of these three types of survey data, and their contributions, are described further. Multibeam sonar data is used to generate three-dimensional digital terrain models (DTM). Sidescan sonar data is used to identify and measure objects on the seafloor. Underwater magnetometer measurements are used to provide information on any distortions on the magnetic field in the survey data, although it "needs to be integrated with other source of underwater information" to be of use (Bodus-Olkowska and Wawrzyniak, 2017).

The authors describe their progress in combining these three data types into a single visualisation format, believing that this "integration allows for a complete modeling of the underwater environment" (Bodus-Olkowska and Wawrzyniak, 2017). Three datasets are added to one another and this is achieved using a layering system, similar to that used in digital image editing software. No additional visual combination is completed beyond adjusting layer opacities. Each dataset is given a hierarchical priority which can change across projects to suit the desired outcomes. Though each survey dataset provides different information, the authors believe that combining each of these offers a more complete view of the survey location, and therefore offers better understanding and interpretation of the underlying data. To achieve the best quality visualisation, Bodus-Olkowska and Wawrzyniak (2017) state that "the highest possible resolution should be used". With Dean et al. (2010) presenting a process for acquiring the best resolution survey data, it encourages an awareness of resulting data quality throughout all stages – acquisition, processing and visualisation – allowing for the greatest amount of flexibility during visualisation.

The proposed method of combining data elements shares similarities with the approach proposed by Chapman et al. (2010), though with one significant difference. Bodus-Olkowska and Wawrzyniak (2017) believe the representation of data to be incomplete when not combined with another survey method, where Chapman et al. (2010) supplement the survey method with additional "special effects".[19] Whilst it is

[19] The multibeam sonar data is supplemented to reach a different and non-technical audience. With a focus on clarity, realism, and accessibility, supplementing the survey data is a choice based on aiding understanding, rather than trying to 'complete' a dataset.

true that each additional survey methods offers additional information, it is not necessarily true that each survey method relies on the others to be successful. Multi-beam sonar is regularly used as a single survey method, though it is not unusual for side-scan sonar to be acquired alongside multi-beam sonar (where each type of imaging is used for different purposes and the datasets are not layered). The most important point of consideration is the increased cost of using more than one survey method simultaneously – similar to considering specialist or standard multibeam, where each serves a purpose, it is more appropriate (and cost-friendly) to consider the combination of methods as an option and select a solution which is tailored to specific requirements.

5.1.3 Additional findings

A number of additional findings were observed throughout the literature review, relating primarily to a lack of available publications or sharing of knowledge in key areas. This section identifies each of these topics as contributions to the overall development of the research and the research themes (chapter 3).

Most of the literature focused on the equipment and software used to acquire and process subsea survey data. Whilst these form critical elements in a modern surveying workflow, there was often a lack of detail in the description of developing and understanding visualisation techniques,[20] beyond showing a finished outcome. This lack of published material was particularly noticeable when moving beyond traditional screen-based methods and creating physical models using sonar data. Though creating digital surface models for 3D printing can be particularly challenging

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[20] In reflecting on practice undertaken collaboratively, the author found this to be the approach both academically and commercially – where maintaining the ability to offer a *unique product* is of great significance, often resulting in a lack of sharing at the forefront of subsea visualisation practice.

when faced with poor quality sonar data (Campos et al., 2011; am Ende, 2001), it becomes fully achievable (though is still often a manual process[21]) when the acquisition and processing stages gather data which supports visualisation through 3D printing. Just as it is essential for *visualisers* to understand data acquisition and processing, it becomes increasingly important for *surveyors* to understand visualisation and its requirements.

Forming a significant point of interest, the literature often mentions the quality of subsea survey data, with reference to its limitations as a reliable or consistent data source. However, there is little *detail* associated with this, and the definitions of good and bad data continue to lack clarity, remaining largely subjective. Without clearer definitions, it is difficult to ascertain or compare the quality of a dataset, the value it holds, and the type of visualisations it can be used for. There were no observable systems or scales which could be used to evaluate or grade subsea survey datasets. Though these may exist in the form of commercially sensitive in-house documentation,[22] such grading systems are unlikely to exist in the absence of clearer definitions and criteria associated with assessing sonar datasets.

Finally, in creating visualisations, there was reference to custom visualisation tools (Chapman et al., 2010). This suggests that standard or 'off the shelf' software packages did not offer all of the functionality that is required in working with subsea survey data. The authors practice confirmed that software packages regularly used by the industry partner, such as CloudCompare or Maya, did not offer a complete functionality when working with multibeam sonar data – this included 'basic' tasks

[21] This is further explored by the author in section 7.5.2, and was also noted in the responses gathered from *Expert A* in the expert interviews study (appendix 14.4).

[22] It was suggested that these may take the form of "metrics derived from processing software: i.e. total propagated error", by *Expert B* in the expert interviews study (appendix 14.4).

such as using Maya to load point cloud data. However, these types of visualisation tools have not been shared or made available for use, or further development. It is the authors view that this is likely due to practitioners trying to maintain a commercial advantage.[23] Though sharing *everything* should not be expected (particularly in a commercial environment), the author believes that sharing subsea visualisation tools (similar to the preference for *open access* to literature in academia) could prove beneficial to visualisation practitioners – instead of progress being hampered by having to start from zero, it would allow development of visualisation tools to build on those that already exist, where the focus can remain on addressing new problems rather than solving those which have already been solved elsewhere.

With an awareness of these topics combined with the limited number of available publications in the field of subsea surveying, a number of additional methods were employed as part of the contextual review to triangulate knowledge and confirm any gaps identified.

5.2 Extended bibliography

With a lack of published material directly relevant to this research, additional literature was sought using the keywords shown in Table 5.1, adopting a more flexible approach to the combination of these to broaden results. An extended bibliography is included in chapter 13, detailing the additional sources which have contributed to the overall knowledge and understanding employed by the author during the research activities.

Figure 5.2 shows the frequency of relevant topics occurring during the extended bibliography. Some sources overlapped multiple topics and so each topic is

[23] An example of this is the WreckSight application created by the 3DVisLab and used exclusively by ADUS DeepOcean.

presented individually, rather than as a breakdown of a single combined total. Though these items have not been cited directly, they have informed the author's thought processes and practice, and helped triangulate knowledge as discussed throughout this chapter. General findings are presented in this section, followed by further exploration of a number of additional topics (such as metadata or land-based survey methods) in the remaining sub-sections.

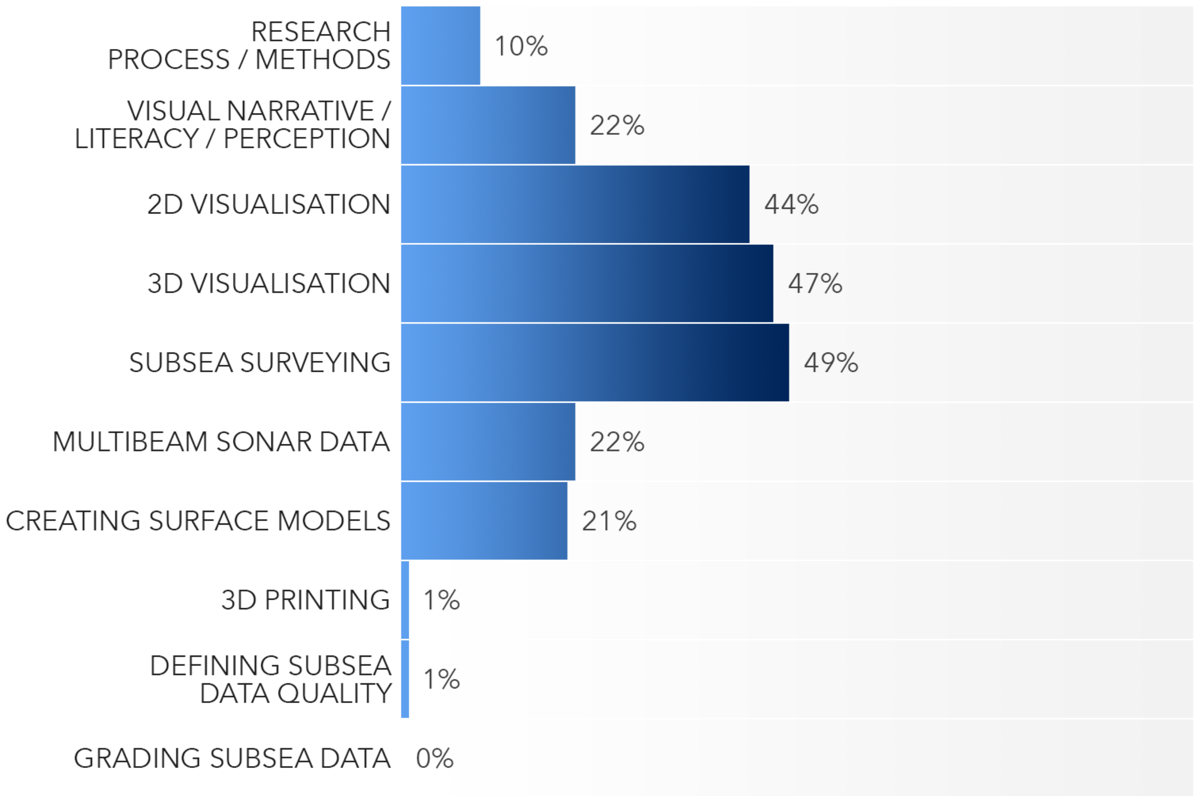

Figure 5.2: Frequency of the topics explored as part of the extended bibliography

An important point to note is that 47% and 49% of sources held some relevance to either 3D visualisation *or* subsea surveying respectively, and there was a number of other sources which looked outside of these areas of study. Despite this, there continues to be very little published material which addresses some of the key issues identified during the literature review.

The use of multibeam data was discussed in 22% of the sources, though the focus of published material was typically on using laser or photogrammetry data. As defined in section 4.4, the scope of this research is on working with multibeam sonar. Though there can be some crossover in knowledge, multibeam sonar data encounters a unique set of problems including significant issues with data noise and resolution. In addition, there is a lack of colour, texture, or facing information. These problems are encountered far less frequently (and often not at all) when using other survey methods, and so literature based on laser or photogrammetric data becomes less relevant when it is discussing and resolving a set of problems different to those faced when working with multibeam sonar.

Similarly, many of the books and articles described the reconstruction of digital surface models from survey data – however, useful results were generally achieved when using photogrammetric data. As discovered during the literature review, multibeam sonar continues to be difficult to surface automatically and often remains a manual process. The extended bibliography uncovered no new literature which helped to resolve issues when surfacing multibeam sonar data, other than an implicit suggestion of gathering higher resolution, more accurate datasets.

With a distinct absence of publications, 3D printing subsea survey data remains a mostly unseen topic, both in the technical processes required to achieve this but also in any comparison or advantage when 'reading' or understanding printed datasets. A single paper described the creation of plastic moulds (used for creating prosthetics and orthotics), though this was based on the use of digital surface models created from quality photogrammetric data. The process of 3D printing was not discussed, and with no reference to addressing the inherent data quality issues with multibeam sonar data. This should be considered a gap in knowledge identified by the author, and is further explored in the practice-led case studies. These case studies were undertaken throughout 2013-2015, where experimental 3D printing took place (documented in chapters 7 and 8). A conference paper was later published by the author summarising the Troll case study work, including 3D printing multibeam sonar data (Gauld, 2015).

Additional work was also undertaken by the author to compare the communicative value offered by 3D printing subsea survey data when compared to screen-based techniques (forming the basis of the Troll workshops detailed in section 7.6), as there were no sources of literature discussing this topic. More recently, an article by Koslow (2016) presented work undertaken by Wessex Archaeology, describing it as "one of the first-ever underwater archaeological sites to be replicated with 3D printing". Unfortunately, the article did not discuss the printing process or types of problems encountered, or fully explore the advantages of 3D printing over other visualisation techniques.

Finally, as shown in Figure 5.2, the extended bibliography uncovered virtually no literature discussing the definitions of subsea survey data quality or how to grade these types of datasets. Although one source briefly discussed data quality, it was in the context of assessing synthetic aperture sonar[24] and did not contribute to any of the topics within the scope of this research. It is important to note that neither the literature review nor extended bibliography found any publications related to grading or evaluating subsea survey data.

5.2.1 Metadata

In its simplest form, *metadata* is defined as "a set of data that describes and gives information about other data" (Lexico, no date-b). It can be used to identify, describe, and locate data and is used widely to provide structure and offer interoperability, particularly in libraries, museums and archives. Good metadata can be used to "find data, use data, and preserve and re-use data in the future" (UNC, 2019), and metadata

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[24] Synthetic aperture sonar is a more advanced version of side-scan sonar, and was assessed using criteria such as how linear the sonar path of travel was, and by evaluating the resulting image sharpness – criteria which cannot be applied to multibeam sonar data.

quality can be established using seven dimensions: completeness, accuracy, provenance, conformance to expectations, logical consistency and coherence, timeliness, and accessibility (Witten et al., 2010). These dimensions are common across both metadata and data, and contributed to the author's development of the Dundee Scale (chapter 10).

There are different types of metadata: descriptive, such as *title* or *author*, typically used for finding or understanding resources; administrative, including technical (such as *file type* or *creation date*) or rights metadata (such as *copyright status* or *license holder*); and structural (used to record relationships – for example, a *sequence* of pages forming a chapter, or an object's place in a *hierarchy*) (Cornell University Library, 2002). Metadata can be stored and shared in two main ways: as a record in an accompanying database (often encoded using XML[25]) or embedded within the file itself. Some embedded metadata is included in almost all file formats and is typically used for technical metadata, though some file formats (and in particular, digital media formats such as JPEG or MP3) also allow descriptive metadata to be embedded (Witten et al., 2010).

To better understand the potential of metadata, Zuiderwijk et al. (2012) undertook a significant review of metadata literature and identified key advantages and disadvantages. Their findings showed the use of metadata to be beneficial for a number of reasons, and these are summarised below:

- Accessibility – better preservation of data for future use, and improvements in data access for those other than the creator.
- Discovery – improved ability to search for and locate resources.

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[25] XML, or eXtensible Markup Language, is one of the most widely-used formats for sharing structured information, described as a "simple text-based format for representing structured information: documents, data, configuration, books, transactions, invoices, and much more" (W3C, no date).

- Interpretation – improved order and organisation, leading to easier analysis and clearer decision making.
- Linking – similar resources can be grouped, duplication can be located and removed, and legacy resources can be integrated.

However, NISO (2017) contributes a more holistic view of metadata quality, writing that metadata is "only useful if it is understandable to the software applications and people that use it". This suggests that metadata standards must be widely accepted across an industry, otherwise the inclusion of metadata offers no real benefit and could complicate datasets unnecessarily. In a review of metadata undertaken by Zuiderwijk et al. (2012) additional challenges were highlighted:

- Costs – creating metadata is expensive and very time-consuming. There are also other costs which could be incurred, such as sensitive metadata being shared alongside data unwillingly.
- Interpretation – consistency can become an issue when provisioning considerable amounts of metadata. There is also the risk of decision-making being negatively influencing because of incomplete or inaccurate metadata.

Technological advances have led to a "vast amount of information being generated, processed, and transferred in the 21st century" (NISO, 2017) and so there is a growing reliance on automatically generating metadata, and on standardising syntax, vocabularies and content – potentially addressing the challenges identified by Zuiderwijk et al. (2012). By achieving a higher level of automation, the human costs associated with creating large amounts of accurate and consistent metadata could be reduced. Widespread standardisation would allow data to be easily transferred across different teams or companies, and provide a framework for an organised library or catalogue of data to be created (even if only for internal use).

In the context of subsea surveying, the deliberate and purposeful use of metadata is extremely limited. Metadata entries could take a number of forms, such as information on the specific survey equipment being used, recording the survey weather/water conditions, guidance on the overall survey quality, or additional notes on the structure or location (such as visual inspection notes, points of interest, etc.). Much of this information is already evaluated and recorded throughout a project, but is not preserved or linked to the resulting datasets (which are generally treated as the primary outcome) and is often misplaced.

As a result, datasets often mean very little to those who were not directly involved in their acquisition or processing, beyond offering some sort of three-dimensional point cloud for examination. All of the datasets provided in the author's accompanying data repository are indicative of ongoing industry practice and deliverables – where files are provided 'as is' with little or no accompanying metadata. Where metadata *is* provided, it has typically been generated and embedded automatically, and includes such fields as who created the file or when it was last modified[26]. As a practical example, a typical point cloud dataset is supplied as one or more XYZ files – this is essentially a basic ASCII text document, where each line of text is a single coordinate with X, Y, and Z values in 3D space[27]. There is no header or supplementary information or detail. When these points are loaded simultaneously (in software such as CloudCompare), they form a complete artefact, structure, or location with no broader context beyond the data points visible on-screen.

Based on the benefits outlined above by Zuiderwijk et al. (2012), the use of metadata could prove advantageous to the offshore industry. Once established, it would allow companies to easily maintain a centralised and detailed record of projects and datasets, with links to relevant documents and media (such as daily weather reports

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[26] This, however, is not even particularly useful as data files are regularly segmented, combined, and transferred throughout a project.

[27] Additional fields can be included alongside the XYZ spatial values such as RGB colour values, though these are not provided as part of multibeam sonar data as these devices cannot collect colour information.

or inspection videos/photos). With improvements in storage and organisation, files would be easier and quicker to locate, and duplication would be reduced. These have all been challenges encountered by the author during the commercial projects undertaken.

However, during a series of online interviews (appendix 14.4) undertaken by the author, industry experts were asked to identify any guidance they were familiar with on best practice, including the use of metadata, when working with subsea survey data. *Expert A* and *Expert C* confirmed they had not encountered the use of metadata, and *Expert B* mentioned "in house procedures" without any further detail. During practical experiences with ADUS DeepOcean and the 3DVisLab, the author saw no evidence of the intentional use of metadata.

This raises an essential question – if the use of metadata could prove to be beneficial, why has it not been adopted in the subsea surveying industry? With such a strong commercial focus, the most likely reason for the absence of metadata is that it is simply not a client requirement. In a fast-moving industry where costs are high and deadlines are strict, the commercial focus continues to be on successfully meeting a client brief whilst maximising profit margins. If clients are not requesting or using metadata alongside their datasets, it is unlikely that any surveying company is going to spend additional time and resources on a project which can be successfully delivered, when other projects are waiting to be started.

There are also additional factors which need to be considered. Many subsea survey companies consist of a small number of specialist core staff, hiring contractors to fill project teams as required. This helps manage project downtime and costs effectively, though it means that survey teams are very rarely consistent. As a result, there is often no unified or consistent approach to completing and returning project documents, or organising and storing project assets. While this is not a significant problem on a series of smaller or one-off projects, it can become exponentially more challenging across larger projects or when trying to connect multiple projects.

Though a standardised approach could be implemented, this requires significant additional time and expense, which a small company may not have the resources for.

Additionally, even where a survey company may have invested in a thorough and consistent use of metadata following clearly defined standards, it would mean very little beyond their own company without a broader set of industry standards or guidance being adhered to. As the offshore industry relies on transferring completed data to a variety of clients, any lack of alignment in metadata standards would quickly become apparent. It is the author's belief that without an industry-wide, agreed upon effort to implement some type of guidance or standards, it will be virtually impossible to successfully implement the use of metadata beyond internal use only. With no-one leading such an effort at the moment, many subsea survey companies are continuing with their 'tried and tested' working practices and are falling behind the innovations found across other industries.

5.2.2 Paradata

In the fields of computer-based visualisation and cultural heritage, the term *paradata* is used to describe information documenting the ways in which 'data objects' have been understood and interpreted by human processes. Examples of paradata include "descriptions stored within a structured dataset of how evidence was used to interpret an artefact, or a comment on methodological premises within a research publication" (London Charter, 2009).

In a review of the history of paradata, Huvila (2012) describes advances since the 1990s as "relatively few", though does believe the most significant step forwards to be the creation of the London Charter. Conceived in 2006, the London Charter is described as a "means of ensuring the methodological rigour of computer-based visualization" when researching and communicating cultural heritage (London Charter, 2009). It contains a number of objectives and principles covering topics such as implementation, documentation (including paradata), and sustainability. As part of the London Charter, paradata is further clarified as the documentation of process, where "evaluative, analytical, deductive, interpretative and creative decisions" should be disseminated in such a way that the relationships between sources, knowledge, reasoning and outcomes are understandable (London Charter, 2009). Bentkowska-Kafel et al. (2012)[28] add to this, stating that transparency and paradata must become an integral part of heritage visualisation practice before it can be "recognized as a valid scholarly method for studying and presenting cultures of the past".

Beyond the use of paradata, the London Charter aims to establish the use of 3D visualisation as a robust and rigorous research method, and is intended to be relevant not just to cultural heritage but to "all those disciplines where 3D visualisation rightfully belongs as a methodology" (Beacham et al., 2006). Unfortunately, the cited intention of this broader application of the London Charter is inconsistent, with both the related publication and the Charter reinforcing a focus on cultural heritage (Bentkowska-Kafel et al., 2012; London Charter, 2009). This could quite easily divert the interest of potential practitioners who are based in other disciplines.

Despite claiming considerable success, The London Charter has not yet been widely adopted. The University of Cambridge hosted an interdisciplinary workshop that included the attendance of three of the original London Charter team, describing the progress of 3D visualisation for cultural heritage as not having been "commensurate with advances in digital technology" and where "few 3D visualizations measure up to the Charter's guidelines" (London Charter, no date). Several possible reasons for this have been identified.

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[28] Each of these authors are, or were, members of the London Charter team.

Huvila (2012) criticised the knowledge-based contributions to the London Charter, believing them to be based on work undertaken in "the early 2000s and before". With modern visualisation experiencing rapid technological advances and changes to the state of the art, a clear understanding of the benefits gained when applying the Charter to modern practice is critical, and would likely improve accessibility and uptake amongst practitioners. Otherwise, at first glance and without thorough inspection, the London Charter could easily seem outdated and distanced from current visualisation practice, particularly when it offers a 2009 *draft* as its latest version.

It is the author's view that the London Charter offers a set of largely theoretical guidelines, with little or no bearing on practical implementation. There is also a lack of subject-specific guidance resulting in a set of broad principles which may not necessarily always be relevant or useful across disciplines. Trying to apply all of these principles could quickly intimidate or overwhelm those new to the Charter. Huvila (2012) also supports this view, believing that "the charter needs to be complemented with practical guidelines and techniques to realise its potential". However, it should also be noted that beyond cultural heritage, there is a distinct lack of published material detailing the practical application of the London Charter, or outlining clear benefits achieved in doing so. Exemplar case studies may prove useful in better promoting the use of the London Charter and its principles (such as the use of paradata), providing practical insight on resolving challenges and smoothing any transition or implementation period.

When considering recent visualisation practice undertaken by the subsea surveying industry, the author's experiences did not find any evidence or knowledge of the use of paradata, or the explicit application of the London Charter and its principles when using subsea survey data. Additionally, when asked as part of a series of online interviews (appendix 14.4), industry experts provided no responses indicating familiarity with paradata or The London Charter. Accordingly, the author suggests that paradata experiences the same challenges in adoption as metadata (presented in section 5.2.1). This is most likely because subsea surveying companies maintain a strong commercial and competitive – often secretive – approach to the surveying projects they undertake, particularly when disclosing their processes or deliverables. This approach does not align well with that proposed by the London Charter, which instead looks towards research, communication, and dissemination.

5.2.3 Other marine data standards

With regards to the 3D visualisation of subsea survey data, Rowland (2010) tells us that “very little research has been published in this field”. Little has changed in the decade since this statement was made, as has been detailed throughout this contextual review chapter, and finding literature directly relevant to both visualisation and subsea surveying continues to be a significant challenge (excluding the work published by the author and those directly involved in this research). The scope of this thesis remains focused on two key areas of development: grading and evaluating the quality of survey data (including better defining ‘good data’ as there is no single, unified view on what criteria this should include); and developing the industry’s visualisation practice by offering technical solutions to common processing and visualisation issues[29] when working with multibeam sonar data.

In addressing these research topics, the author identified two publications, which both offer standards or best practice: the *London Charter* (London Charter, 2009), and *Marine Survey: A Guide to Good Practice* (Niven et al., no date). Though they are not directly aligned with the aims of this research, as the closest examples of marine

[29] Though subsea survey acquisition is discussed throughout, the scope of this research does not include developing acquisition quality – this has already been progressed significantly by the industry collaborator and its partners (ADUS DeepOcean, 2016; Dean et al., 2010; Bates et al., 2010).

data standards their relevance and contribution to the research practice will be reviewed.

The London Charter was previously introduced alongside paradata (section 5.2.2) and offers a set of principles for "the use of computer-based visualisation methods and outcomes in the research and communication of cultural heritage" (London Charter, 2009). These principles cover a range of topics and are largely intended to improve transparency during the documentation and dissemination of visualisation research. However, the creators of the London Charter made a conscious decision not to offer field-specific guidance; in their '*Commentary on The London Charter, 2.1*' the creators state that their goal is to address "methodological issues at quite an abstract level" rather than make "highly-specific technical recommendations" (London Charter, 2012). This lack of technical guidance and application was previously noted as a significant shortcoming by Huvila (2012). In an article by Hermon et al. (2007), the applicability of the London Charter was tested and reviewed using two cultural heritage projects; though the authors emphasised the importance of the rigour and structure offered by the London Charter, they described its application as "difficult when dealing with multi–disciplinary projects" and criticised a lack of detail in coping with the different pipelines and methodologies employed during different forms of data acquisition.

In returning to the author's research focus, the London Charter does not attempt to define or improve definitions of good data, offer ways in which this can be evaluated, or identify the factors which are essential in doing so. Instead, the London Charter offers a more holistic and theoretical approach to 3D visualisation throughout. Although a structured and methodological approach to visualisation practice is essential, the focus of this thesis is on grading data and offering technical improvements to visualisation practice – the London Charter, in its current form, does not contribute to addressing or further developing these issues.

Marine Survey: A Guide to Good Practice is an online guide containing three sections, with the authors describing their intended purpose as addressing issues in the "archiving and preservation of survey data generated as part of marine archaeology projects" (Niven et al., no date). The first section introduces the guide document and its aims, providing a clear background and rationale for the preservation of the marine historic environment. A series of internet links are provided and these refer to various bodies governing archaeology and oceanography, though the links generally lead to further information on depositing maritime data in archives. Section two provides a brief introduction to marine survey techniques and makes a number of suggestions on topics such as choosing the best file format, the importance of documenting the data process, and creating metadata. Finally, the third (and largest) section provides significant detail on archiving marine survey data. This includes deciding what data should be preserved, providing guidance on how to structure an archive, and addressing ownership and copyright.

However, while *Marine Survey: A Guide to Good Practice* provides a concise yet thorough resource, with links to a significant number of related standards and documentation, its scope and relevance to this thesis are narrowed by maintaining focus on the long-term preservation of marine data. The guide offers a clear description of good practice in addressing archiving data, but offers no practical suggestions related to data acquisition or quality beyond a broad suggestion of thoroughly documenting the processes undertaken. This is a surprising approach, as the host of the online guide suggests that high quality data[30] should be used for preservation or archival purposes, though the guide offers no recommendations or

[30] The Archaeology Data Service hosts a number of online guides, including *Marine Survey: A Guide to Good Practice* (Niven et al., no date). The ADS describes itself as "an accredited digital repository for heritage data that supports research, learning and teaching with freely available, high quality and dependable digital resources" (ADS, no date).

best practice on how to gather high quality data, or what constitutes high quality data. Additionally, it should be noted that although the online guide includes a short overview of sonar acquisition techniques, this is not accompanied by any real-world or practical application. There are also no subsea data evaluation criteria offered, or examples of the quality of data which could be suitable for depositing in an archive. As a result, *Marine Survey: A Guide to Good Practice* (Niven et al., no date) does not contribute to the focus of this research, which remains on improving the grading and 3D visualisation of subsea survey data.

Finally, during a series of online interviews conducted by the author (provided in appendix 14.4), subsea industry experts did not identify any other marine data standards or relevant guidance which could be used to inform this research and the creation of the Dundee Scale (chapter 10).

5.2.4 Land survey methods

Subsea survey methods have been presented in sections 4.4 and 4.5, though these are not the only survey methods which can generate point cloud data. There are also a number of land-based survey techniques that result in three-dimensional point cloud data, and in some cases, digital surface models. The most common of these are laser scanning and photogrammetry.

5.2.4.1 Laser scanning

Laser scanning, also known as LIDAR (**LI**ght **D**etection **A**nd **R**anging), is a remote sensing method which uses lasers to measure distances. Similar to SONAR, a series of signals – using light instead of sound – are pulsed outwards and their reflections on objects and surfaces are recorded (this is referred to as a 'time of flight' method). These reflected signals are then combined with additional information from GPS and

IMU[31] systems, recorded simultaneously, to "generate precise, three-dimensional information" in the form of point cloud data (NOAA, 2020). Where multibeam sonar can be considered "centimetric at best" (Rowland, 2010), terrestrial laser scanning can achieve "centimetric to millimetric resolution" (Jaboyedoff et al., 2012). Laser scanning can also be used as an aerial survey method, though the resolution of the resulting point cloud data is likely to be lower as the scanning device is usually significantly further from the object or location being scanned. In their review of LIDAR systems, Jaboyedoff et al. (2012) describe the resolution of airborne laser scanning as "metric to decimetric". A thorough description of 3D laser scanning, titled *3D Laser Scanning for Heritage: Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture*, was published by Historic England (2018) and contains 16 case studies detailing a range of applications and variant technologies, including their typical accuracy and range.

5.2.4.2 Photogrammetry

Photogrammetry is defined as the "use of photography in surveying and mapping to ascertain measurements between objects" (Lexico, no date-c). Photogrammetry is frequently used in fields such as architecture, engineering and cultural heritage, and is used to generate high-resolution point clouds and digital surface reconstructions. It is important to note that, typically, three-dimensional data is created from a series of two-dimensional images using a photogrammetric technique called *structure from motion*. Westoby et al. (2012) describe a typical working process (resulting in a "fully georeferenced, high-resolution, photo-realistic DEM"[32]), summarised as follows:

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[31] *Inertial Measurement Units* are used to provide detailed navigational information (such as position, heading, and velocity) using accelerometers and gyros.

[32] A Digital Elevation Model, or DEM, is a 3D representation of a surface or terrain, commonly used in geographic information systems to produce relief maps.

- Image acquisition – for the best results, this should result in a series of high quality photographs from multiple angles, with overlapping coverage and consistent lighting (as much as is practically possible).
- Keypoint extraction – points of interest are automatically identified across photographs, allowing features to be matched across images.
- 3D reconstruction – camera poses are estimated, and keypoints are used to match images and triangulate 3D locations, resulting in a point cloud dataset.
- Post processing – includes georeferencing, or transforming a relative object to an absolute co-ordinate system. Translation, rotation and scale are critical factors here, as scan data is placed back into a real-world location. Gridding or subsampling may be introduced to ensure datasets remain manageable.
- Surface model creation – a digital model is created from the resulting point cloud data, and the original photographs are used to apply photorealistic colour and texture.

Unlike a large amount of subsea data processing, many of these working stages are completed automatically and there a number of competing software packages which can be used, such as Agisoft Metashape or 3DF Zephyr. Though only an overview of photogrammetry has been presented here, the application of photogrammetry and structure from motion as survey methods has been widely researched and documented (Carrivick et al., 2016; Konecny, 2014; Luhmann et al., 2013).

5.2.4.3 Differences between subsea and land survey methods

There are significant differences between subsea and land survey methods. Rowland (2010) summarises these as "resolution, noise and colour".

As already identified by Jaboyedoff et al. (2012), the resolution of land-based laser scanning is far higher and can be millimetric, where multibeam sonar is no better than centimetric, often missing this target resolution because of factors such as unpredictable weather. Although there are high-resolution subsea laser scanners available (such as those available from industry leader *2G Robotics*), multibeam sonar continues to prove effective as a subsea survey method because it uses sound instead of light, and is therefore not affected by poor visibility in the way that an underwater laser scanner would be (Dobson, 2016). However, all subsea survey methods – whether laser or multibeam – continue to be affected by uncontrollable factors, such as the significant movement of the survey vessel, and this is something that is an ongoing problem and can result in inconsistencies in data resolution.

Noise is a notable difference between land and subsea survey techniques, and has been previously highlighted as one of the most significant challenges when working with sonar data[33]. Point cloud data gathered using multibeam sonar data regularly suffers from high levels of noise and often requires a large amount of additional post-processing – this is due to "changing temperature and detritus found in the water column" during data acquisition (Rowland, 2010). Land survey methods are not affecting by such factors (where water conditions are no longer relevant), and so there is a higher likelihood of gathering datasets containing little or no noise.

In contrast to multibeam surveying, terrestrial laser scanning[34] and photogrammetry offer an additional benefit by also capturing colour information and detail, which can be applied to any resulting point cloud datasets or digital surface models. This provides an immediate improvement to the recognisability and clarity of objects and locations in point cloud form, which can often be abstract or unclear without additional information. It is not possible for multibeam sonar equipment to be supported by the same optical systems which gather colour information, as the quality of these is significantly impacted by poor visibility and loss of colour saturation (where the quality is most affected at higher water depths).

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[33] During a series of online interviews conducted by the author (appendix 14.4), industry experts identified these as noisy data, poor coverage, positioning/motion reference and the speed of post-processing.

[34] When "supported by optical systems" (Rowland, 2010).

It is clear that subsea survey methods encounter a unique set of challenges which land-survey methods do not. As a result, the visualisation of land-survey methods has advanced beyond the visualisation of subsea survey methods. The scope and aim of this thesis is to address problems identified when working with multibeam sonar data, and many of the offered solutions and practical knowledge are applicable only to subsea survey data. However, there are a number of outcomes which are suitable for re-application – whether that be to land or aerial survey methods. For example, the visualisation tools (provided in appendix 14.2) can be used to load[35] or edit point cloud data, regardless of the data acquisition method.

5.2.5 Scan to BIM

Scan to BIM is described as "the process of 3D laser scanning a physical space or site, to create an accurate digital representation", that can then be used for "designing, assessing progress or evaluating options" (The B1M, 2017). The process consists of two key stages: collecting data using a laser scanner, followed by incorporating this into a BIM process. BIM, or *Building Information Modeling*, is described as a "process that allows multiple stakeholders to collaborate on the planning, design, and construction of a building within one 3D model" (Constructible, 2018). Unlike traditional graphics-oriented CAD processes, Building Information Modeling adopts a database-centric approach - providing connected resources and recording changes made, using a central digital location. Described as the "overarching approach to

[35] The *loadWreckRGB1* (appendix 14.2.2) and *loadWreck255* (appendix 14.2.3) scripts were created in response to a need to load XYZRGB data into Maya, and were created to assist a member of the 3DVisLab in loading point cloud data containing RGB colour information, gathered using photogrammetric techniques as part of a cultural heritage research project.

implementing BIM in the UK", the UK BIM Framework sets out standards and guidance for implementing BIM (UK BIM Framework, no date).

The Scan to BIM process offers a number of advantages – in particular, the use of laser scanning improves the surveying process by reducing human error and allows high volumes of data to be collected in a shorter period of time (Constructible, 2019; The B1M, 2017; Autodesk, 2002). As a result, survey data can be quickly acquired and shared with other project members. In addition, survey teams should only need to visit a site once to collect survey data. Using a centralised repository of data and documents can also reduce duplication, and allows changes to be followed throughout a project lifecycle. Each of these benefits contributes to an overall cost-saving provided by the implementation of a Scan to BIM project framework. Autodesk describes the use of BIM as important because it offers efficient workflows and visualisations, improving "project coordination and collaboration with stakeholders" (Autodesk, no date).

However, despite offering clear advantages and showing significant adoption rates in the construction industry[36], Scan to BIM sees little or no usage in commercial offshore practice. The most likely reason for this is that the Scan to BIM process involves the use of high-resolution, noise-free building data gathered using laser scanning techniques, where subsea surveying does not typically employ laser scanning and faces a number of unique challenges in generating accurate, clean and reliable data (section 5.2.4).

In addition, the offshore industry has shown further concerns related to the adoption of a Scan to BIM process. Murphy (2016) notes that despite clear cost-saving benefits

[36] In their National BIM Report, the National Building Specification state that the "overall trends of BIM awareness and adoption have grown from little more than 10% in 2011 to around 70% in 2019" (NBS, 2019).

"there has not been a sector-wide drive to adopt BIM type systems in offshore renewable energy". Possible barriers have been identified as: a reluctance to share information in a commercial environment, contractual and legal constraints limiting the sharing of assets, and the required additional investment in new systems, training, and technology (Murphy, 2016). Furthermore, in an article exploring the offshore implementation of BIM, Ray Crotty "argues there is no place for BIM in the offshore sector", and develops this idea further suggesting that "using BIM could even endanger rig workers"[37] where projects are already less fragmented than their onshore counterparts (Offshore Technology, 2017). These responses to Scan to BIM are indicative of the ongoing debate in the offshore industry – clear benefits have been identified, but companies remain largely unconvinced that the benefits outweigh the costs.

Though the application of a Scan to BIM framework offers several advantages over traditional CAD techniques, the author's research is concerned with addressing the inherent challenges faced when working with multibeam survey data, and improving and extending the working processes and techniques employed by the industry collaborator ADUS DeepOcean. Until these data challenges are addressed, adopting a Scan to BIM framework is unlikely to offer any further commercial improvements.

5.3 Creative practice

The author's creative practice was primarily undertaken whilst working as part of commercial projects with the industry partner, ADUS DeepOcean. Some additional follow-up work was completed, using a bank of datasets from the completed projects. Three of these projects were chosen for further discussion and are included

[37] Crotty states that unless "you can keep the [BIM] model and the physical platform completely in sync, the model becomes dangerous, a source of error, a potential risk" (Offshore Technology, 2017).

in the form of three case study chapters, leading to the creation of the *Dundee Data Grading Scale* (chapter 10). Using practice as research relied on the author's reflection and evaluation, and this was employed to confirm or deny the findings of other contextual review methods.

During each of the commercial projects, the author noted the regular use of multibeam sonar to produce two types of digital output – two-dimensional visualisations (e.g. PDF charts), or three-dimensional interactive visualisations (e.g. WreckSight). The 3D interactive visualisations were presented as a more advanced solution, and as a result of a specialist multibeam survey being undertaken. There was no current or previous indication of 3D printing as an alternative visualisation method, and neither ADUS DeepOcean nor the 3DVisLab had explored this as a viable option. Though 3D printing was already commonplace in other industries, the author noted slow adoption rates in the offshore industry, accompanied by a lack of literature (sections 5.1 and 5.2), and as such this topic formed one of the primary themes developed in later research activities.

It was also observed by the author that there was no unified or clear approach to defining the quality of subsea survey data. Even with some views suggesting that data density or accuracy were some of the most important factors,[38] there was no agreement or guidance on how accurate data needed to be, or how many points would provide an appropriate point cloud density. There was also no identified literature which set out clear definitions of good or bad subsea survey data. Improving the definition of subsea survey data quality became one of the goals of this research.

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[38] Views on such topics varied across projects and teams – examples can be found in the expert interviews *Section C* responses (appendix 14.4).

In conjunction with defining the quality of data, it was determined that a system for evaluating or grading datasets would be required. As with the literature review and extended bibliography, the author's practice did not find any such systems in use, and so this topic was chosen as a significant area for development.

5.4 Industry experts

In addition to the author's reflection and evaluation, further triangulation of the contextual review findings was undertaken. This took the form of online interviews completed by industry experts identified during the author's commercial projects. This online approach was chosen in place of traditional interviews as the chosen experts regularly work remotely and were difficult to arrange face-to-face meetings with. The completed interviews can be found in appendix 14.4, with key points relevant to the contextual review summarised in this section.

One of the key issues previously identified was the subsea surveying industry's slow adoption of 3D printing. The results of the expert interviews proved to be useful in better understanding this reluctance, where participants were asked to choose from a range of seven visualisation techniques and identify those that were regularly provided as client deliverables. The responses showed that 3D printed physical models were not regularly provided as client deliverables, with no selections from experts (Table 11.1). In addition, when asked, there was no indication that they would like to see 3D printed physical models used less often, and only one industry expert indicated that they would like to see 3D printed physical used more often (Figure 11.3).

This result is most likely because participants considered the production of 3D printed physical models to be the most expensive solution. During the expert interview questions, experts were asked to order seven visualisation methods from 1 to 7, with 7 representing either the most expensive solution (question B2) or the most communicative value (question B3). Figure 5.3 and Figure 5.4 present these responses visually, with each bar representing the values averaged across all of the expert responses.

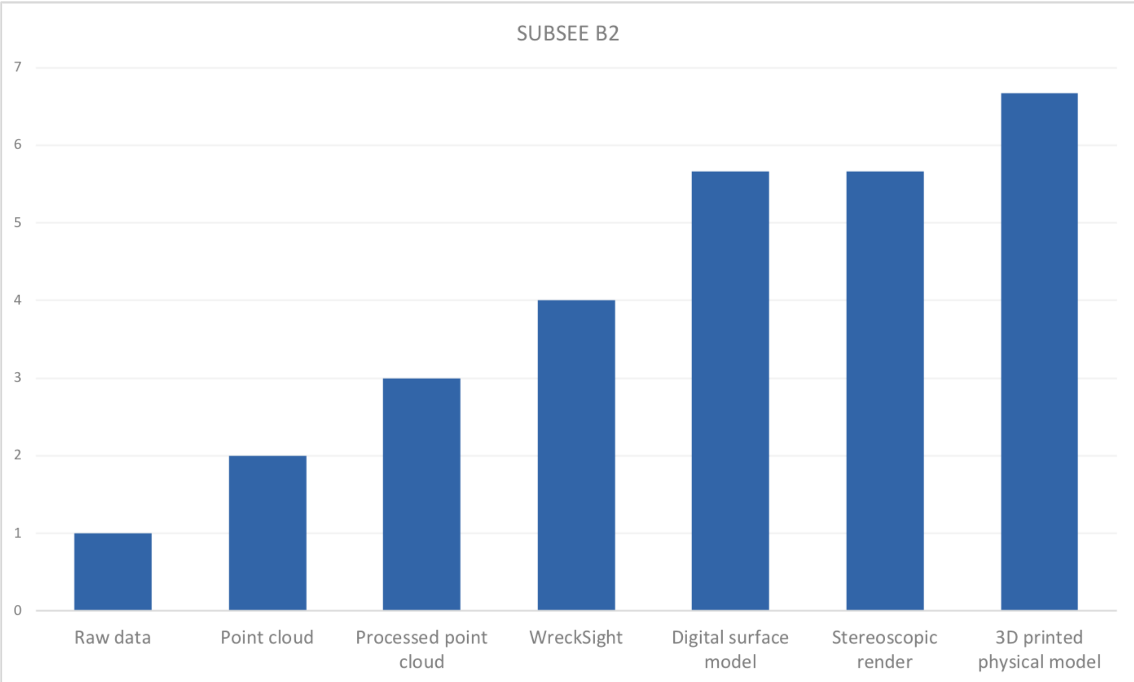

Figure 5.3: Graph showing the averaged responses given to expert interviews question B2 (most expensive solution)

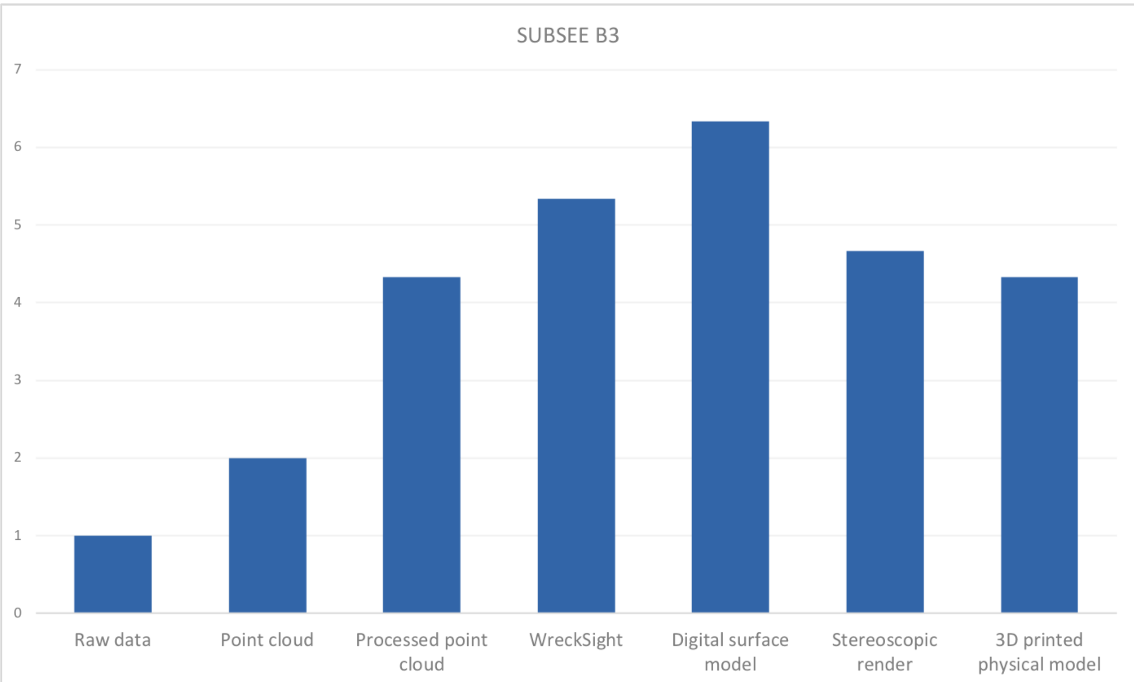

Figure 5.4: Graph showing the averaged responses given to expert interviews question B3 (greatest communicative value)

Despite this increased perception of cost, participants did believe 3D printed physical models to offer a level of communicative value higher than other methods (placing joint fourth), though not the highest overall which was shown to be the use of digital surface models.

However, creating digital surface models using multibeam sonar data continues to be a significant challenge due to ongoing issues with data quality. As a result, there is a reliance on creating surface models manually,[39] and this is the most likely cause of increased production costs. The expert responses identified a number of challenges when working with subsea survey data,[40] and these aligned with the author's own practical experience and other published materials.

As the literature review and extended bibliography uncovered no useful sources on best practice, participants were also asked to identify any guidance on best practice, including the use of metadata or paradata, that they may have encountered when working with subsea survey data. *Expert A* (more than 11 years of experience) and *Expert C* (more than 15 years of experience) were not aware of the use of any of these, while *Expert B* (over 25 years of experience) referred to the use of "in-house procedures", though with no detail of what these may entail.[41]

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[39] During the expert interviews, *Expert A* suggested that processing beyond raw data is "significant" and "often manual". This aligns with the authors practical experience, and with the views found in the literature review and extended bibliography, in particular relating to the creation of digital surface models using automatic methods.

[40] Such as facing issues with noisy data, poor coverage, positioning/motion reference and the speed of post-processing (responses given to question C3, expert interviews).

[41] ADUS DeepOcean was voluntarily liquidated in January 2019, and so access to any internal documents or detailed processes is no longer possible.

Finally, participants were asked if they were aware of any methods of grading or evaluating subsea survey data. *Expert A* had no awareness of existing subsea data grading systems, and *Expert B* again referred to the possible use of in-house procedures, suggesting these may relate to "metrics derived from processing software: i.e. total propagated error". Though useful, such measurements do not form part of a unified grading scale or system which can be used to evaluate and compare datasets consistently.

5.5 Summary

This chapter has presented a contextual review which underpins the research themes and has directed the research activities towards answering the research questions. As there is a limited amount of relevant published material available, a multi-method approach was taken, and the contextual review was developed and expanded alongside and throughout the research practice.

A number of key problems have been identified, explored, and triangulated, resulting in a set of goals summarised as follows:

- Improve understanding of visualisation outputs and their value (e.g. communicative value versus cost to produce).
- Increase automation, in particular the creation of digital surface models.
- Develop the subsea visualisation pipeline (with the inclusion of 3D printing and understanding its value).
- Define data quality and how this can be graded consistently.

In chapter 4, a background to the research was explored, providing a historical view of data visualisation and details the acquisition, processing and visualisation of subsea survey data. Chapter 5 develops this with a discussion of current industry trends, and the challenges faced by modern practitioners. Together, these chapters provide a rationale for the research activities and the methodology employed.

6 Methodology

This section describes the methodology used by the author throughout this doctoral research. Using the ideas set out by Frayling (1994), this work should be considered *research through art and design*, where the research has structured elements of development, action, and communication, separating it from research *into* or *for* art and design. In establishing the author's methodological framework, recommended and relevant PhD theses were also reviewed and compared (Birnie, 2014; Rowland, 2010; McGhee, 2009), and a multi-method approach was adopted throughout the research.

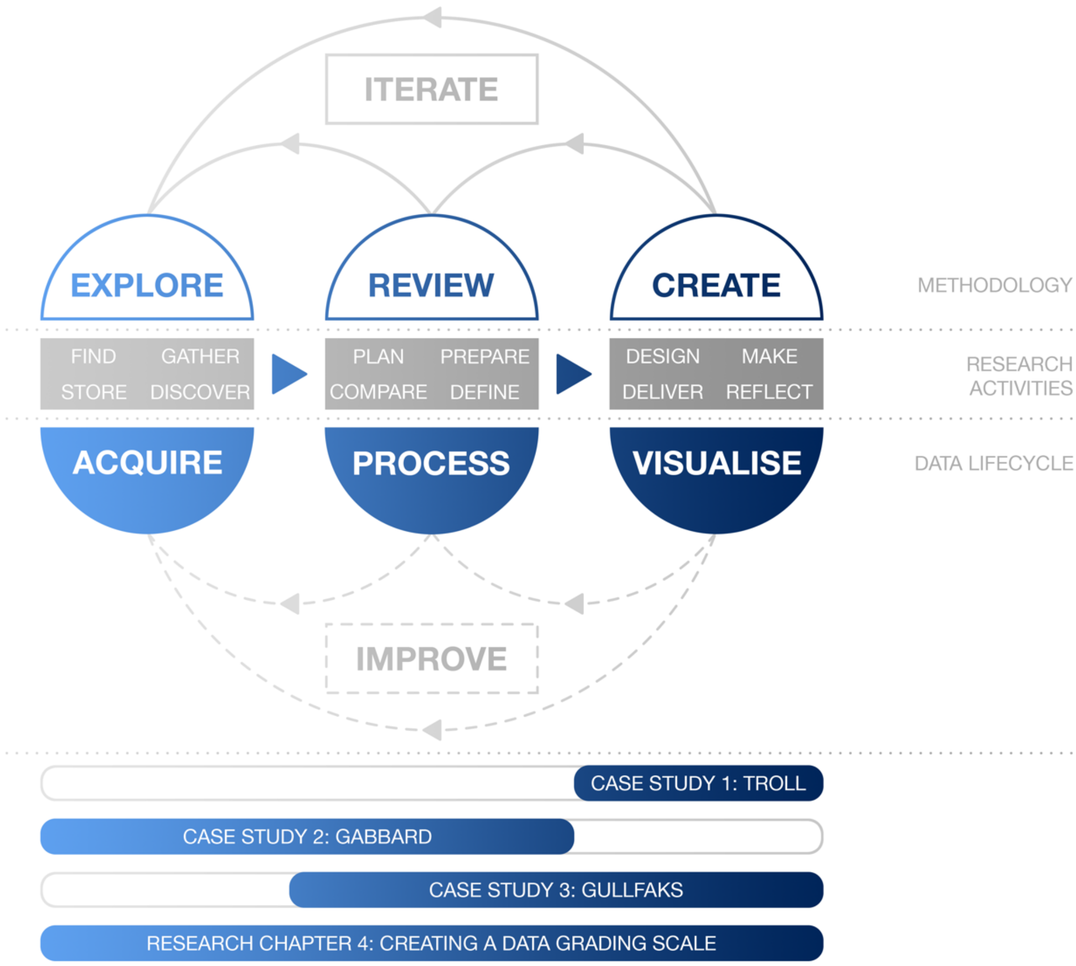

*Figure 6.1: '**Explore Review Create**' framework, alongside the typical data lifecycle, and completed case studies*

Figure 6.1 shows the author's developed and adopted methodological research framework – named **Explore Review Create**. The diagram shows these three stages mapped alongside the data lifecycle[42] (introduced in section 4.5), and the related research activities that each stage typically consists of. The 'improve' lines are dashed because it is not always possible to return to earlier stages of data visualisation.[43] Finally, each of the three case studies later included in this investigation (chapters 7, 8, and 9) and the fourth research chapter (chapter 10) are shown as part of this diagram and related to each of the data lifecycle stages. It is important to note that each of these stages – acquisition, processing, and visualisation – are always relevant, but each chapter has a particular focus.

In developing and understanding this methodology, several key existing approaches were considered and combined (discussed further in the following sections). As a result, the **Explore Review Create** framework shares similarities with other familiar approaches relevant to 3D visualisation – such as 'discover design develop deliver', often found in fields such as service or experience design. This practical approach was also realised from the intersection between reflective practice and action research, creating opportunities for research to be both broad and specialist at different stages of the process. Crucially, it allowed for ideas to be questioned and developed based on existing research and established methodologies – where the results of multiple methods can be 'triangulated' and examined from a number of different viewpoints, creating a more complete outcome (Gray et al., 2004).

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[42] This refers to the identified *acquire*, *process*, *visualise* steps of working with subsea survey data.

[43] Due to the costs of subsea surveying, if data collection is rushed or acquired poorly, it is often the only attempt made to capture a dataset, and so no attempt to *improve* the acquired data can be made.

Applying this knowledge to the use of commercially-driven case studies in a real-world research setting created a suitable approach to the author's practice as research, and helped in undertaking the role of research practitioner. This allowed for greater flexibility in approaching the case studies creatively, and also ensured a greater level of methodological robustness as reflection and evaluation took place throughout the entire iterative research process, rather than just on completion – thus creating a repeatable cycle of self-improvement.

6.1 Contributory methodological components

The **Explore Review Create** methodology used throughout this research is multi-method, and the contribution and importance of each method is discussed further in the following sections.

6.1.1 Practice-led approach

Candy (2006) defines practice-led research as research which is "concerned with the nature of practice and leads to new knowledge that has operational significance for that practice". Practice is considered an integral research method, and this type of research typically falls within the area of action research (Boyce-Tillman, 2012; Candy, 2006). Although this type of research can often be fully explained in the form of written text without the need for creative artefacts as a product, the research outcomes are represented both by creative artefacts, their contextualisation and the complete process. There should also be a critical analysis of the outcomes, and a clear contribution to new knowledge. As part of this research, critical analysis and evaluation took several forms: by identifying the commercial success of a project, hosting workshops to broaden awareness and improve visual understanding, through the author's own reflection on practice, and in gathering the views of industry experts via online interviews.

In 2007, the AHRC published a report on practice-led research in the arts (Rust et al., 2007). This was the result of a ten-month investigation, and included their own definition of research led by practice – "research in which the professional and/or creative practices of art, design or architecture play an instrumental part in an inquiry." Undertaking creative practice (in the form of processing and visualisation subsea survey data as part of commercial projects) was a critical component of this research – without completing this type of work, the author would have no relevant or applicable knowledge or understanding of the issues being faced by industry practitioners. During their investigation, Rust et al. (2007) used a variety of methods which would form a similarity with this visualisation research, including workshops (discussed further in section 7.4.1, and applied throughout section 7.6) and case examples (further explored in section 6.1.6, and forming the basis for case study chapters 7, 8, and 9).

This idea of practice as research was further developed by Rust et al. (2007), stating that the research should focus on how the creation of an artefact[44] allows the researcher to focus on and examine issues and concerns that practice alone may not otherwise reveal. Finally, it was said that "in a research setting, the knowledge associated with the artefact is more significant than the artefact itself" (Rust et al., 2007). This is particularly relevant to subsea surveying – where the working processes repeat with each new commercial project and new knowledge can continually be developed and re-applied.

Due to the practical and cyclic nature of this doctoral research, a practice-led approach to research has been essential, allowing new ideas to be considered, tested

[44] Throughout this research, the *artefact* typically takes the form of 3D visualisations created by the author (whether that be a digital deliverable or perhaps resulting in a 3D printed object) with the steps involved in developing each artefact to be considered creative practice.

and implemented. Barrett and Bolt (2007) state that "*new* knowledge in creative arts research can be seen to emerge in the involvement with materials, methods, tools and ideas of practice." This new knowledge is revealed through the creation of visual artefacts, as part of an interactive process of experimentation and creation, coupled with evaluation and reflection.

Most importantly – without creative practice, any visualisation research would be based only in theory and it would be difficult to truly improve the way subsea survey data is being presented.

6.1.2 Multi-method research

> "A diversity of imperfection allows us to combine methods, not only to gain their individual strengths, but also to compensate for their particular faults and limitations. The multimethod approach is largely built upon this insight. Its fundamental strategy is to attack a research problem with an arsenal of methods that have non-overlapping weaknesses in addition to their complementary strengths." (Brewer and Hunter, 2006)

Sitting at the intersection between 3D computer graphics and subsea surveying, this research is considered interdisciplinary in nature (Choi and Pak, 2006). As a result, it felt only natural that a multi-method approach would be used to strengthen the methodological validity of any findings. The multi-method approach adopted throughout this research therefore incorporates a variety of established elements drawn from a number of disciplines, creating an iterative process of question and answer leading to improved problem solving, implementation and understanding.

There are also elements of 'naturalistic inquiry' – a research paradigm which encourages the researcher to carry out research in a more natural situation, where the research has been given time to "emerge, develop, unfold" rather than be pre-designed (Lincoln and Guba, 1985). This approach works particularly well within art and design, as it does not try and force a particular outcome – it encourages creativity and allows for the unexpected to be embraced. Naturalistic enquiry pairs well with the use of 'real-world' case studies – such as those which took part in a commercial setting – where unexpected challenges or outcomes arose beyond that of an overly-structured or laboratory-type environment.

6.1.3 Reflective practice

Described as an "alternative to the traditional epistemology of practice" (Schön, 1991), reflective practice encourages a process of continual learning where actions and outcomes are reflected upon and examined both as research is being undertaken and as deliverables and conclusions are generated.

Reflective practitioners believe that experience alone does not necessarily provide new knowledge, and only when combined with deliberate reflection can a higher level of understanding be achieved. This reflection will often encompass research actions and outcomes, emotions, responses and opinions, with a focus on combining all of these elements to improve the integration of theory and practice, and provide a clearer understanding of process and results.

In understanding the need for reflective practice, Schön (1991) makes an important point, saying that "because each practitioner treats his case as unique, he cannot deal with it by applying standard theories or techniques." Throughout the author's research, the role of reflective practitioner has been adopted as a critical component, helping inform and direct the continuing research actions and activities. This approach has also been implemented alongside design research and action research methods as they each encourage a cyclic and iterative process of self-improvement.

6.1.4 Design research

"No single research methodology could possibly account for the diversity of inputs and outputs to contemporary design practice and process. There are simply too many markets and media, clients and users, ways and means." (Laurel, 2003)

Design research describes a wide collection of investigative techniques, which can be used to improve design and research processes, gaining greater insight through practice and developing better outputs based on experimentation and iteration. Curedale (2013b) states that using design methods and thinking allows "a designer to balance both analytical and creative thinking processes concurrently", helping to promote effective working as part of a cross-disciplinary team. Design research is both reflective and cyclic in nature, where outputs can become inputs, and typically follows the stages shown in Figure 6.2.

Figure 6.2: Typical iterative design research process, adapted from an original diagram by Maier (2010)

Design research provides a methodological approach which encourages practice-led learning, one where "acts of making and reflection can occur along the entire length of the process" (Sanders and Stappers, 2014). This is of particular importance as it encourages critical evaluation during all stages of the research process, rather than just an analysis of a finished product. In this sense, it creates additional opportunities for knowledge and learning to be extracted and then applied, therefore improving both the process and the product. Maier (2010) tells us of another benefit of using a design research approach, where it can "combat the natural tendency to design for ourselves (or our stakeholders) rather than designing for our target audience", ensuring that we, as designers, don't "tend towards a self–serving, uninformed design process".

An important part of this design research cycle is extracting feedback on the prototypes and practice through testing. Throughout this research, there were several key methods of doing this – such as understanding the success of a commercial project through fulfilling or exceeding the client's expectations, collecting user responses and opinions on visualisation (both expert and non-expert), and by conducting interactive workshops.

Although a design research approach is being applied throughout this research, it is important to note, however, that in this instance design research is being applied as part of a methodology enabling a structured approach to creativity, visualisation problem solving, and reflective practice-led learning, rather than creating a new contribution to the development of design research methods.

6.1.5 Action research

Similar to design research in nature, action research refers to a reflective process of working which encourages reflection and evaluation throughout a practical process. Smith (2007) described action research as "research oriented toward the enhancement of direct practice" – or learning by doing.

The term 'action research' has its origins in the 1940s, and Kurt Lewin is considered to have coined the term in 1944, with it also appearing in his 1946 paper titled "Action Research and Minority Problems". Lewin was a German psychologist, often considered the "founder of social psychology", and was a pioneer in multiple areas of study, including organisational development and group dynamics.

Smith (2007) tells us that Lewin believed that research "that produces nothing but books will not suffice" – this view helped develop the principles of action research, as its primary focus is to encourage practical experimentation, rather than rely solely on more 'traditional' research methods.

Despite this distancing from traditional research methods, O' Brien (2001) stated that action research still has an emphasis on being scientific and providing some structure, separating this type of research approach from others. More specifically, it was described as the researcher adopting a systematic approach to problem solving, spending time evaluating and refining the "methodological tools to suit the exigencies of the situation".

As part of the **Explore Review Create** methodology used by the author, the principles of action research contributed to creating a cyclic research process, where new knowledge was re-applied throughout the process, so that the final 'products' – whether that be new knowledge or a visualisation prototype – were strengthened and iterated by the work being undertaken.

As with the use of design research, it is important to note that action research has helped define this doctoral research and structure the process and outcomes, rather than create a new contribution to the development of action research methods.

6.1.6 Case studies

Employed specifically as an exploratory research method, the use of case studies provides a means of structuring research and is particularly relevant in addressing research in real-life situations. Yin (2009) describes a case study as "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context" – that is, an approach that recognises that the context is often as relevant as the phenomenon itself. This is in contrast to the more traditional 'laboratory experiment' approach where context and phenomenon are deliberately divorced in an attempt to control or manage the expected variables.

The use of case studies as part of this research aligns well with the project-driven nature of subsea survey data – where three different commercial projects form three distinct case studies, each addressing different research themes while also identifying similarities and patterns. Similarly, due to the 'live' commercial nature of these projects, they cannot be constructed and undertaken as controlled experiments and so a different research method must be used which supports this approach and offers the best means of generating new knowledge and understanding in doing so.

6.1.7 Real-world research

Robson (2011) describes real-world research as applied research rather than pure or basic, and suggests that there is a distinct focus on solving practical problems, working in the field, and orienting research to client needs. This approach synergises well with the use of practice-led case studies.

As part of multiple commercial projects, the author was provided with a unique opportunity to witness work being undertaken, where new challenges are encountered and critical elements are not always successful. Stepping outside of a theoretical grounding, this provides first-hand experience of any problems which may need to be resolved in an attempt to deliver a finished product on-time for a client, and enables a cyclic process of problem solving and self-improvement – generating new knowledge and understanding in the process – which might not otherwise have been visible, possible or necessary in a controlled environment.

6.2 Applying the Explore Review Create framework

With the **Explore Review Create** framework structuring and informing the author's research practice, this section will consolidate the application of this framework to the research, offering a clearer view of the work undertaken.

The goal of this investigation was to explore and develop the 3D visualisation and grading of subsea survey data – using three case studies where existing techniques are first *explored* and *reviewed* against one another, identifying which are of the most value, followed by the *creation* and ongoing cyclic iteration and *review* of the application of newer techniques. Additionally, a fourth research chapter consolidates the *exploration* and *review* of data grading techniques as part of the *creation* of a system for grading subsea survey data.

Task	Explore	Review	Create	Chapter
Develop understanding of data visualisation and subsea surveying	E			4
Create/refine research questions and themes	E	R		2, 3
Identify research methodology	E	R		6
Review literature	E	R		5
Undertake case study practice	E	R	C	7, 8, 9
Acquire data	E			
Data processing	E	R		
Visualisation		R	C	
Create a data grading scale	E	R	C	10

Table 6.1: Application and summary of the author's ***Explore Review Create*** *framework*

Table 6.1 details each of the key stages of this investigation, showing which part of the **Explore Review Create** framework was most relevant (though they all played a role in each research activity), and identifying which chapters discuss each topic fully (rather than repeat information here). It is important to note that this table does not present a linear order in which tasks were necessarily undertaken as parts were revisited and iterated throughout.

As the **Explore Review Create** framework consists of a number of contributory methods, Table 6.2 shows the application of each of these methods to the research questions. It is important to note that all methods were used while addressing the research questions, though some had a much smaller role and the table shows the most significant applications. Research question zero has been included to show the overall importance and contribution of each method.

	RQ0	RQ1	RQ2	RQ3	RQ4
Practice-led	•••••		••	•	••
Multi-method	••••	•	•	•	•
Reflective practice	••••		••	••	
Action research / design research	••••	•	•	•	•
Case studies	••••••	••	•	•	••
Real-world research	•••	•			••

Table 6.2: Application of contributory research methods to each of the research questions

6.2.1 Evaluating the research outcomes

A number of methods were employed in evaluating the research and its outcomes. These methods were selected due to their relevance in evaluating 3D visualisation research as shown in similar theses (Rowland, 2010; McGhee, 2009). These methods include the use of workshops (section 7.4.1), expert interviews (section 10.5) and reflection on practice (section 6.1.3) and are referred to and used throughout the research activities and case studies.

6.3 Summary

In this chapter, the methodology used by the author throughout the following case studies has been introduced and communicated visually, and its contributory elements and their application have been explored in greater detail.

Using the **Explore Review Create** framework has enabled the author to combine a number of recognised research methods to create a multi-method approach suitable for application to 3D visualisation practice as research. Although now presented as a complete process, it was generated incrementally as the research was undertaken and iterated and improved using the cyclic nature of action research as an exemplar.

In addition to using this methodology throughout the case studies, the simplified visualisation workflow (first introduced in section 4.5) has also been included when mapping the methodology visually as it shares some similarity with the research process. Although the entire visualisation workflow is relevant in all three of the case studies, each maintains a particular focus throughout, as originally shown in Figure 6.1. Finally, Table 6.1 and Table 6.2 were included to further explain two sets of relationships: how each of the research chapters has been approached as part of the **Explore Review Create** framework, and the direct relationships between each of the research questions and the methods employed in addressing these.

6.4 Introduction to case studies

In the following chapters, three case studies will be examined – each discusses the author's involvement in a different commercial project working with the industry sponsor ADUS DeepOcean, and is based upon the application of 3D visualisation techniques to subsea survey data. The work undertaken as part of each commercial project forms the basis of the author's creative practice – where subsea survey datasets are used to create a series of 3D visualisations. These can be used alongside other methods to critically evaluate both the process and outcome of each case study, contributing new knowledge to the ongoing practice of subsea surveying and 3D visualisation.

Although the case studies are numbered, they will be primarily referred to using their project names – Troll, Gabbard, and Gullfaks (Figure 6.3) – which originate from the locations that the survey data was acquired.

TROLL (CASE STUDY 1) **GABBARD** (CASE STUDY 2) **GULLFAKS** (CASE STUDY 3)

Figure 6.3: Image identifying each of the case studies alongside their respective visualisation dataset and outcomes

As the first of the case studies, the primary focus of the Troll project was on visualising a dataset which had already been acquired, and processed by the 3DVisLab. This allowed the author to focus solely on creating different ways of presenting the data, which would later be compared and evaluated. This also enabled the introduction of techniques such as stereoscopy and 3D printing, in turn providing a better practical understanding of what would be required in creating these types of visualisation from subsea survey data.

Building on the knowledge gained during the first case study, the author undertook a second commercial placement with ADUS DeepOcean and the 3DVisLab for approximately three months. This project, titled Gabbard, involved surveying a wind-farm containing 140 offshore wind turbines and was an opportunity to shadow subsea surveyors, observe the data acquisition process, and also undertake the role of data processor. Additionally, it provided access to a library of high-resolution survey data which had been gathered in accordance with the strict guidelines developed by ADUS DeepOcean.

Finally, Gullfaks was a challenging project for ADUS DeepOcean – the goal of which was to generate results from a dataset which had been poorly acquired, one which other contractors had not been able to create useful insight from. The author's primary role, working in collaboration with the 3DVisLab, was in post-processing the data to overcome a series of identified problems with two extremely large datasets (each representing two states of the same structure), so that the resulting data could be visualised and these states could be compared.

7 Case Study 1 – Troll

This chapter will discuss both the Troll commercial project and the following workshops which took place. In addition, parts of this chapter are based on a paper which discusses the experimentation with different visualisation techniques applied to this Troll subsea survey data (Gauld, 2015). The practical work undertaken as part of this case study was initially completed during November/December 2013, with additional follow-on work undertaken at various points throughout 2014 and 2015. The original project was completed in collaboration with the industry sponsor, ADUS DeepOcean.

The following sections will detail the site location and why it was surveyed, followed by an introduction to working with subsea survey data and an exploration of the practice, workshops and reflection undertaken by the author as part of this research case study.

7.1 Troll E4E5

The Troll oil and gas field is located in the North Sea, around 65 kilometres west of Kollsnes, near Bergen, Norway (shown in Figure 7.1).

Troll Gas is currently operated by Statoil, and Troll Oil production is by Hydro. With production starting in September 1995, it originally contained "about 40 per cent of total gas reserves on the Norwegian continental shelf (NCS)" (StatOil, 2007).

However, despite initial opinions that the Troll field would primarily be used for gas production, in 2002 more than 400,000 barrels of oil were being produced each day (StatOil, 2007). In 2005, as part of their first quarter results, Hydro announced that oil production had passed one billion barrels, and they believed Troll to be "one of the largest crude oil producers in the North Sea" (Hydro, 2005).

Figure 7.1: Location of Troll oil and gas field (ABB, 2018)

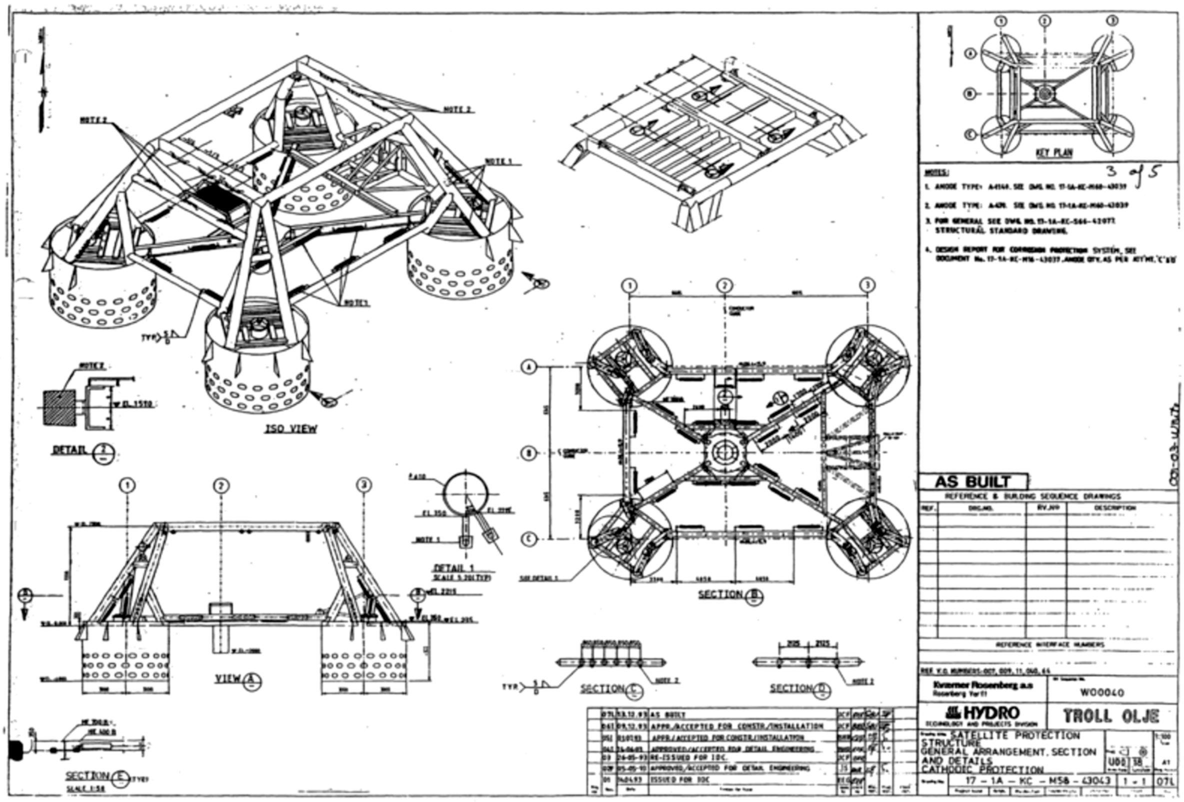

Figure 7.2: Troll 'as-built' paper plans (low-resolution scanned image provided by ADUS DeepOcean on behalf of the client)

The Troll E4E5 data is a survey of a protective structure (protecting a wellhead used for drilling oil), at a depth of approximately 325m. The client wanted to be able to compare the current state of the structure to the original 'as-built' plans (shown in Figure 7.2).[45] Additionally, they wanted to generate a solid 3D surface model which would aid decision-making in their future planning processes.

The use of photogrammetry had been considered by the client as a means of recreating the underwater structure, but was deemed too time-consuming (due to the complexity of the structure combined with underwater visibility issues), and so instead the decision was taken to use multi-beam sonar. DeepOcean, in collaboration with Scopos, gathered data using a Teledyne BlueView multi-beam sonar system, which attempts to use higher frequencies (1.35 or 2.25MHz, as opposed to 200 or 400kHz used by the Reson 7125 more typically chosen by ADUS DeepOcean) in order to generate better quality data (that is, data which is clearer and more accurately records the source).[46] Additionally, an ROV was used to capture video footage of the structure, which could be used alongside the acquired survey data.

Overall, the scanning process lasted around 45 days in total – a considerable amount of time to survey one structure. This was largely due to the scanning method – placing the BlueView sonar device in a fixed location and completing one spherical

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[45] Unfortunately, this was the highest quality version of the as-built plans provided by the client and is largely unreadable. As a result, it was used only as a starting point to help identify the approximate structure in the accompanying sonar data, and was not used beyond this purpose.

[46] During the expert interviews (questions C1 and C2), industry practitioners described the features of good quality subsea survey data: high accuracy, high precision, high point density, low/limited noise, oblique/consistent coverage, and location accuracy.

scan, before moving it to the next location and repeating the process, building up a complete view of the structure. The completed set of scans are shown in Figure 7.3, where each of the scanning locations creates a circular blind-spot and there are a series of these areas containing less data throughout the dataset. By completing multiple 360° scans in this way, the overlap aims to minimise any areas with little or no coverage. Once completed, the data was given to ADUS DeepOcean, allowing their involvement and processing to begin.

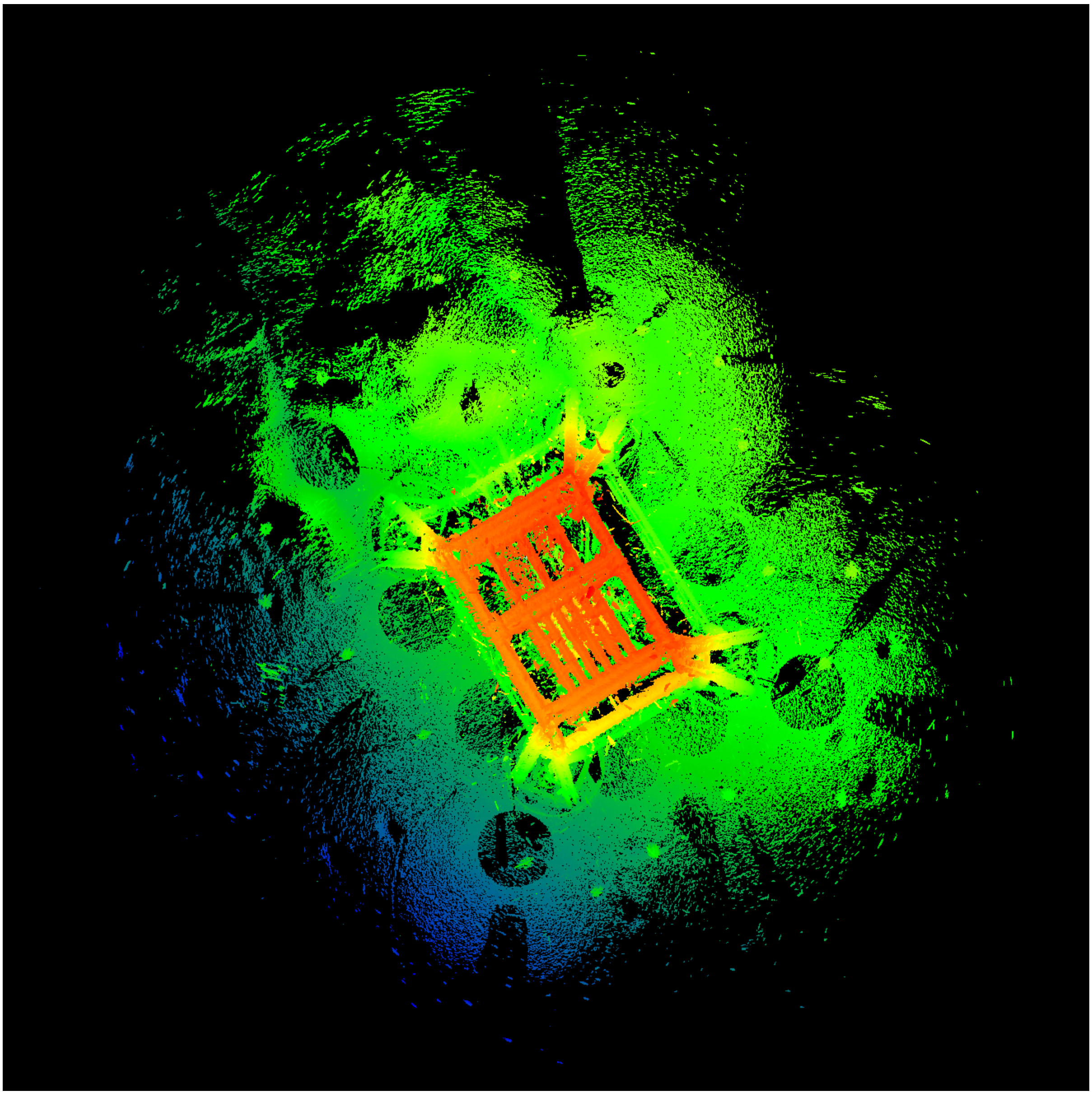

Figure 7.3: Image of the original Troll dataset showing a series of circular scanning blind-spots

7.1.1 Industry collaboration with ADUS DeepOcean

ADUS DeepOcean are part-funders of this research, and have played an important role throughout. As a practicing subsea survey company, working with them ensures that any research undertaken and outputs being generated maintain a commercial relevance and application. Ongoing support from ADUS DeepOcean offers the opportunity to work with both high-quality datasets and industry professionals, enabling a practice-led approach to visualisation of high-resolution subsea data.

Data 7.1: Data repository > CS1 Troll > 01 Raw Data

It is important to note however, that ADUS DeepOcean were not involved in the acquisition of the Troll E4E5 data, which was passed to ADUS DeepOcean only for processing and visualisation (Data 7.1). This data was particularly challenging for a number of reasons: extremely dense overlapping datasets (containing over 122 million points, where the processed version contains ~265,000), high levels of noise in the resulting point cloud, and difficulties in registering/aligning the individual survey segments. On reflection, the entire project would likely have been simpler had ADUS DeepOcean been responsible for (or at least involved throughout) the entire process.

7.1.2 Collaboration with 3DVisLab

In addition to the involvement and collaboration with ADUS DeepOcean, the team at the 3DVisLab (also based in DJCAD, University of Dundee) formed part of the Troll project team. The 3DVisLab were primarily responsible for processing the data on behalf of ADUS DeepOcean, and resolving some minor data quality and alignment issues. Once these data issues had been resolved, the author's involvement began – starting with manually creating a solid 3D surface model from the Troll survey data.

7.2 Research questions

Although the research questions were introduced earlier (section 2), they will be re-visited below and their relevance to the work undertaken during the Troll case study will be examined.

> **RQ0:** Can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?

Research question 'zero' continues to drive the overall direction of the research, and the Troll case study begins to look at the type of subsea survey data and visualisation currently taking place, alongside some of the more varied visualisation techniques available.

> **RQ1:** How effective are current visualisation methods in communicating subsea survey data accurately and clearly?

The workshop section of the Troll case study explores the communicative value that different visualisation techniques can offer, and these can be directly compared based on the findings as part of answering research question one.

> **RQ2:** What is the relationship between automation and 3D visualisation of subsea survey data?

The Troll practice included attempts to automate visualisation tasks, in this case surface model generation – which was not possible with this dataset. The implications are discussed in section 7.5.2, and a solution suggested.

> **RQ3:** What are the effects on the understanding of subsea survey data in the transitioning between digital and physical 3D representations?

The practical work completed during the Troll project offers insight into creating the different types of representations of data, including overcoming any challenges encountered and which parts were more successful. The following Troll workshops offered the ability to gather both qualitative and quantitative data from experts and non-experts when comparing different visualisation techniques, both physical and digital.

> **RQ4:** What is the measurable value of innovation in 3D visualisation to the subsea surveying industry?

This case study offers insight into and comparison between the different visualisation techniques which the subsea surveying industry are currently using and could be using, paired with an understanding of the practical implications of undertaking the visualisation work and the expected benefits of doing so.

7.3 Research themes

Throughout the Troll case study, all five of the research themes (detailed in chapter 3 and visually in Figure 3.1) were addressed to some extent. Although **automation** was further developed, the most relevant were **value** and **digital versus physical**.

7.3.1 Evaluating visualisation techniques

The notion of *value* when considering 3D visualisation techniques continues to be extremely difficult to define, and in many cases remained subjective with no unified approach to measuring value. The Troll practice and workshops resulted in a series of different data presentation types, using the same dataset throughout and allowing for direct comparison between how well they each communicate the underlying data. In this instance, the author refers to the communicative value that the use of different visual techniques can offer – simply, the most valuable visualisation technique being the one that promotes clarity and understanding over the others.

However, as part of a commercial project, value could be interpreted in a more literal sense – if the work being completed in a cost-effective manner, and if not, it is important to explain why not and ascertain what can be done to improve this. Additionally, addressing the needs of a client can be seen as valuable to a contractor, whether they agree that the requested deliverables are of the very best quality or not they are adhering to the client's interpretation of what is valuable, not their own.

Beyond each of these practical explanations of value, Tukey (1977) offers his own, which incorporates all of the above in a broader sense, believing that "the greatest value of a picture is when it *forces* us to notice what we never expected to see".

This does not give us a specific means of measuring value, but instead offers a way of acknowledging an achievement or result and so the most valuable visualisation method is the one that provides us with the greatest amount of discovery.

7.3.2 Automating visualisation

> "What's most needed in the field of data visualization, as in other fields, is not always what's most exciting or not even what's particularly innovative. Sometimes we simply need to make it easier to do those things that work." (Few, 2013)

As part of the Troll case study, almost all of the creative visualisation work was undertaken manually. Through reflection on the practice undertaken by the author, it has been shown that due to the often basic (e.g. low-resolution) yet challenging (e.g. high-noise or incomplete) nature of subsea survey data, manually undertaking some tasks still continues to offer the *only* appropriate means of successfully creating useful visualisations[47].

For example, as subsea survey data can frequently be 'soft' or poorly defined in the way it presents objects, it can be difficult to decide which data points are simply noise and can be removed, and which are part of the object or structure being examined and should be kept. At the time of writing, automatic point cloud cleaning methods are not yet sophisticated enough to perform this type of task reliably – instead they typically remove data evenly from across the entire dataset in an attempt to 'lighten' the density. Whilst subsampling data has its application[48], it does not achieve the same result as somebody who has worked with subsea survey data, is familiar with the structures being displayed, and who can apply their expert tacit knowledge in achieving the best results in preparing and cleaning data for visualisation – the Troll dataset is an example of this, where noise removal was undertaken manually by members of the 3DVisLab.

One time-consuming task completed as part of the Troll case study was creating a 3D surface model of the structure. Using 3D surface models (instead of point cloud data) is of significant benefit to the subsea survey industry, offering clearer views of

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[47] During the expert interviews, Expert A described *raw data* and *unprocessed point clouds* as requiring "significant additional processing, often manual, before a useful visualisation output can be produced" (appendix 14.4.)

[48] Subsampling was used during the Gullfaks case study (section 9.5.2) and can result in 'lightening' extremely dense datasets, significantly reducing the impact on software and hardware performance.

a scanned object or location. This is achieved by addressing the sometimes confusing presentation of point cloud data, where shapes and depth can be difficult to perceive due to the "gaps between points" problem (Rowland, 2010), and by offering a more realistic visual solution through the application of elements such as lighting, colour and perspective (Chapman et al., 2010; Chapman et al., 1999). The creation of a digital surface model also provides access to additional visualisation options, including 3D printing and virtual/augmented reality[49]. During the expert interviews undertaken by the author, the industry experts' responses revealed that digital surface models were viewed as offering the greatest communicative value amongst other current subsea visualisation options (Figure 5.4). *Expert B* and *Expert C* also stated that they would like to see digital surface models used more often, despite increased production costs[50].

However, just as the Troll data could not be cleaned automatically, creating a surface model of the Troll data automatically was not possible. The structure was too complex, featuring a series of circular pipes intersecting one another, instead requiring a surface model to be created manually (this process is detailed further in section 7.5.2). In other circumstances, automating surface model creation using subsea survey data *is* possible, provided the data does not contain any challenging shapes. For example, a relatively flat area of seabed, with no overhanging sections, can be surfaced automatically and in no more than a few seconds once the correct settings have been identified (the Gabbard case study produced two 3D prints created using automatically surfaced datasets, shown in Figure 4.13 and Figure 8.16).

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[49] During the expert interviews, Expert B referred to the wider uses of digital surface models, referring to the Offshore Simulator Centre (OSC) creating advanced simulators for offshore training purposes.

[50] During the expert interviews, Expert C stated that it is "very expensive to process multibeam point cloud data to [a digital surface model] because of the noise and amount of holes in the data" (appendix 14.4).

In contrast, some steps of the visualisation process can be fully automated – such as being able to load point cloud data into Maya. Despite being one of the leading 3D computer graphics and animation software packages, Maya does not natively read point cloud data from external files, and so requires bespoke tools to be created through scripting. As part of the research practice, the author developed three *loadWreck* tools which can be used to load point cloud data in Maya, and these can be found in appendices 14.2.1, 14.2.2, and 14.2.3 (three tools were created to cater for different input file layouts).[51]

Without a tool for loading large files automatically, a user would have to manually 'paint' data points in 3D space, and with a single dataset easily containing millions of points, it is not practical to do this manually. With an optimised and efficient custom-built tool, loading datasets usually takes less than a minute. This is an example of where automating repetitive and non-creative tasks proves immensely useful, and the technology is sufficiently advanced enough to allow this to be possible, without requiring any further manual input beyond selecting which task to run.

7.4 Methodology

Although methodology has been detailed earlier in chapter 6, this was broader in its application as it referred to the overall research and all of the case studies as a whole.

[51] Prior to the author writing the included *loadWreck* scripts, the only data loading tool available to the 3DVisLab was a bespoke Maya plugin (compiled from C++ source code) for Maya 2011 exclusively. It was not useable in other versions of Maya, and some of the source code was no longer available – so this could not be updated or reverse-engineered.

The application of the **Explore Review Create** methodology provided a clear structure throughout this case study. Where existing visualisation techniques were first explored and new techniques were uncovered, these were reviewed against one another (as part of a series of workshops), and in doing so, a set of comparative visualisations were created using one data set throughout (where significant practical knowledge was gained in adopting different visualisation techniques).

In this section, additional methods (beyond those already covered in chapter 6) which were employed specifically as part of the Troll case study will be explored.

7.4.1 Using workshops

Throughout the Troll case study, one particular evaluation method was a critical part of the process – the use of workshops to gather views and opinions from both experts and non-experts.

Described as a "strategic design method" (Curedale, 2013a), the use of workshops as a research tool created an opportunity to gather feedback from participants in a directed or semi-structured way. For the Troll case study, these workshops were created so that both qualitative responses and quantitative data could be used to compare the success of different visualisation techniques. Data was gathered anonymously and from a variety of groups – including animation students, creative professionals, and information technology administrators and practitioners.

Upon completion, the results were collated and analysed – this is discussed in greater detail in section 7.6 which explores all of the workshop elements and outcomes.

7.5 Practice

As the Troll data had previously been worked on elsewhere before it was received by ADUS DeepOcean, the 3DVisLab at the University of Dundee spent some time cleaning and re-organising the datasets before passing them to the author for further development. The author's role in working with the Troll data was to create a surface model from the point cloud, which would represent the underwater structure – this would fulfil the client's requirements, though the author later also undertook some further experimental work using the provided data.

7.5.1 Acquisition, processing, and visualisation

As part of the ongoing research process, the author established a basic model for working with data consisting of three distinct stages – acquisition, processing and visualisation (shown earlier in Figure 4.5). This same model applies to work completed using the Troll data – the author's role was primarily part of the 'visualisation' stage (Figure 7.4), as the data had already been acquired before ADUS DeepOcean started work on this project, and the 3DVisLab had then processed the data ready for visualisation.

Figure 7.4: Author's role in the Troll project

The data was originally gathered using a BlueView multi-beam sonar system – a mechanical scanning sonar which creates "high resolution imagery of underwater areas, structures, and objects" (Teledyne, 2013) – which had been placed in multiple fixed scanning locations around the Troll structure. Each of the locations were then scanned in full circles, generating a series of overlapping almost-spherical datasets. This approach to data acquisition is not uncommon in underwater situations, as it allows a structure to be captured from a variety of different angles and positions, so that there are no empty areas or blind-spots in the resulting data.

These completed datasets were then positioned correctly alongside each other to create a 'complete' structure, and then cleaned – where noise was removed to help provide clarity. Although there are some techniques for automatically removing noise, industry experience gained through working with ADUS DeepOcean has shown that using experts and their tacit knowledge to manually clean data provides stronger results as they can recognise objects where sometimes software cannot, though this approach is more time-consuming.

During the preparation of the Troll data, there were concerns about the quality of the gathered sonar data, particularly where points were recorded at an increasingly greater distance from the scanning location (with the accuracy of these points becoming less reliable further from 'zero' – this can be seen in Figure 7.5, where the scan quality reduces further outwards from the BlueView sonar location). A decision was made by the 3DVisLab to remove all data from each scan segment beyond the point that they were not considered to be entirely accurate, particularly when another scan segment may have been closer and provided 'better' (i.e. more accurate and complete) data points. This also reduced the amount of overlap between scan segments, which would make the overall dataset smaller in size (by reducing the total number of points), and with less uncertain areas to be tidied.

Although this part of the process was not yet the author's focus, it did raise an important point. When acquiring subsea survey data, ADUS DeepOcean have identified 74 factors that need to be addressed (ADUS DeepOcean, 2016). It should be noted that there is not yet a similar approach to data processing, or grading data and whether it is suitable for visualisation. This often results in trying to visualise complex or difficult data, which can require a large amount of processing before results can become possible. It is expected that planning the data acquisition in conjunction with the expectations of how the data will be processed and visualised would prove far more effective, and help eliminate some of the difficult problem solving which may be required later in the process. This issue is discussed again in a later case study, using the Gullfaks dataset (chapter 9), and further addressed in proposing a data grading scale (chapter 10).

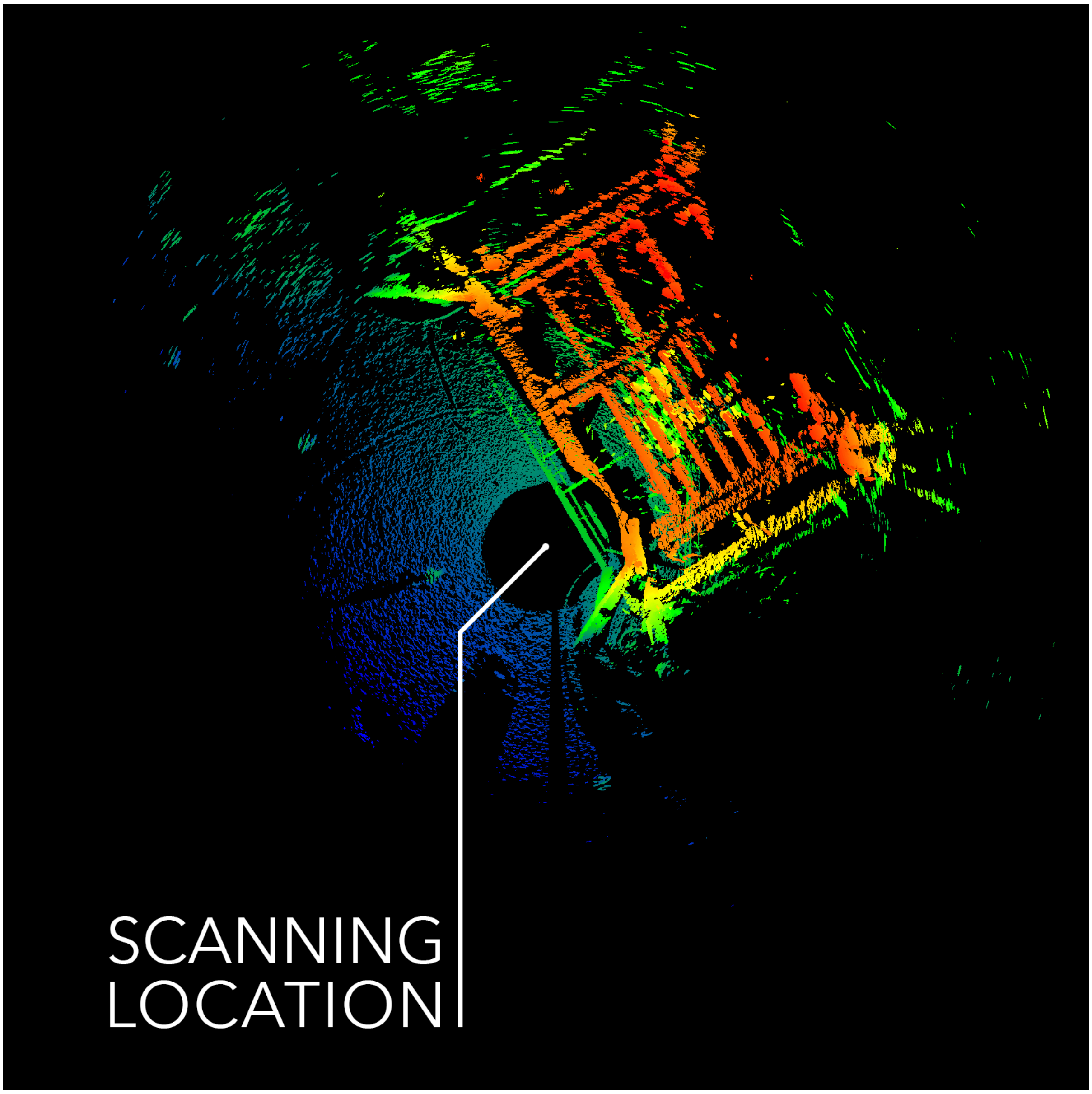

Figure 7.5: Section of Troll dataset showing data quality and density degrading outwards from the central scanning location

After each of the datasets were aligned and cleaned by the 3DVisLab, a final point cloud was provided so that visualisation could begin (Data 7.2). The original brief from the client was to create a digital 3D surface model representing the Troll structure, using the point cloud generated from the multibeam sonar as a base model.

Data 7.2: Data repository > CS1 Troll > 02 Processed Point Cloud > Troll E4E5.XYZ

7.5.2 Surfacing point cloud data

A surface model (mesh) is a recognisable and 'solid' structure which is used to digitally represent the original subsea structure which was scanned using sonar data. This surface model generally gives a better visual understanding when compared to a point cloud, as it provides a clearer idea of depth and makes it simpler to see what is solid and what is not. For example, where a beam or pipe may actually be, rather than just loosely arranged data points which look like a beam or pipe, particularly to an untrained eye.

Figure 7.6 shows the transition between the point cloud and finished surface model versions of the cleaned and processed Troll data – on the left is the point cloud data, where the rough shape of the structure can be seen, though depth is harder to perceive because all of the points look identical. Without any additional context or motion, it would be very difficult to identify specific parts of the structure. The surface model on the right of the image provides a much clearer view of the same data, making the underlying structure more easily recognisable, especially to those not familiar with the structure and how it should look.

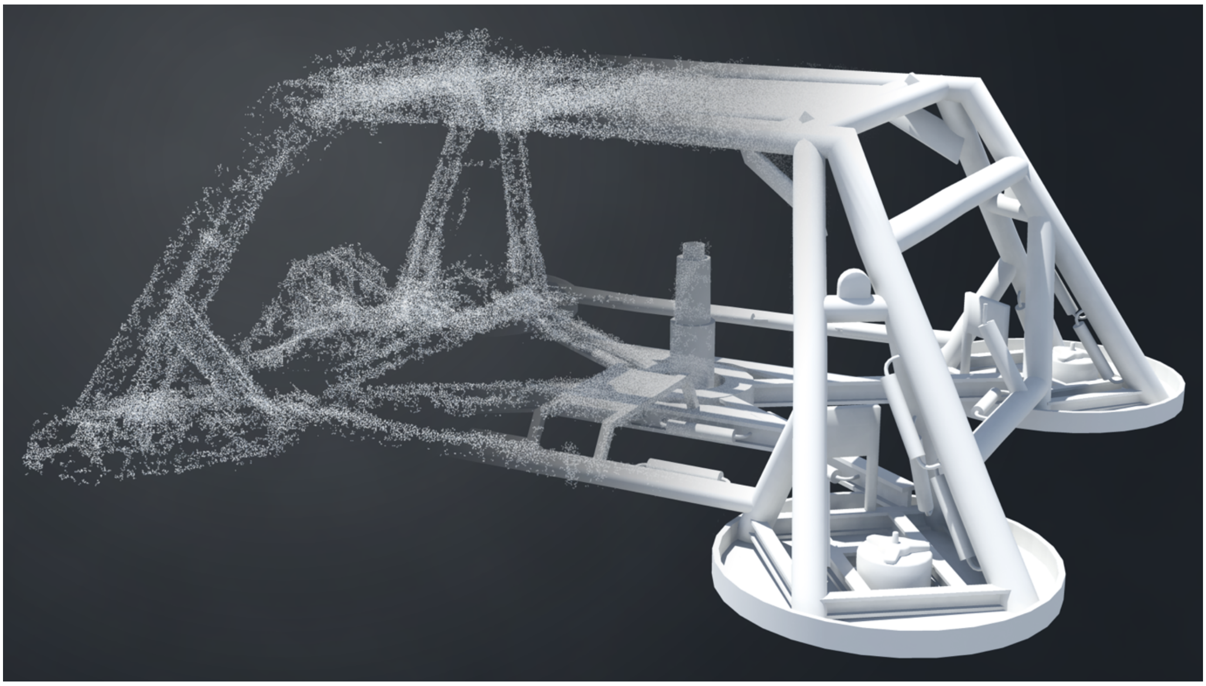

Figure 7.6: Comparison between point cloud and surface model, created using the same dataset

To surface the point cloud, CloudCompare was selected as it formed an essential component in the technical workflows already established by the industry partner.[52] This open source software can be used for both viewing and manipulating 3D point clouds and surface models, and has become widely adopted due to its expanding range of features and high level of support. It features a variety of automated meshing techniques, and these were used first in attempting to create a Troll surface model.

[52] Previous attempts at sharing knowledge with surveyors (in particular, the Maya stages of 3D visualisation) by the 3DVisLab proved unsuccessful. As a result, the author chose to align with the surveyors' existing knowledge and processes, offering the best opportunity in providing new visualisation options. There was also the added factor of cost, where additional software packages would have to be purchased and the business concern was that these would then have seen limited or no use.

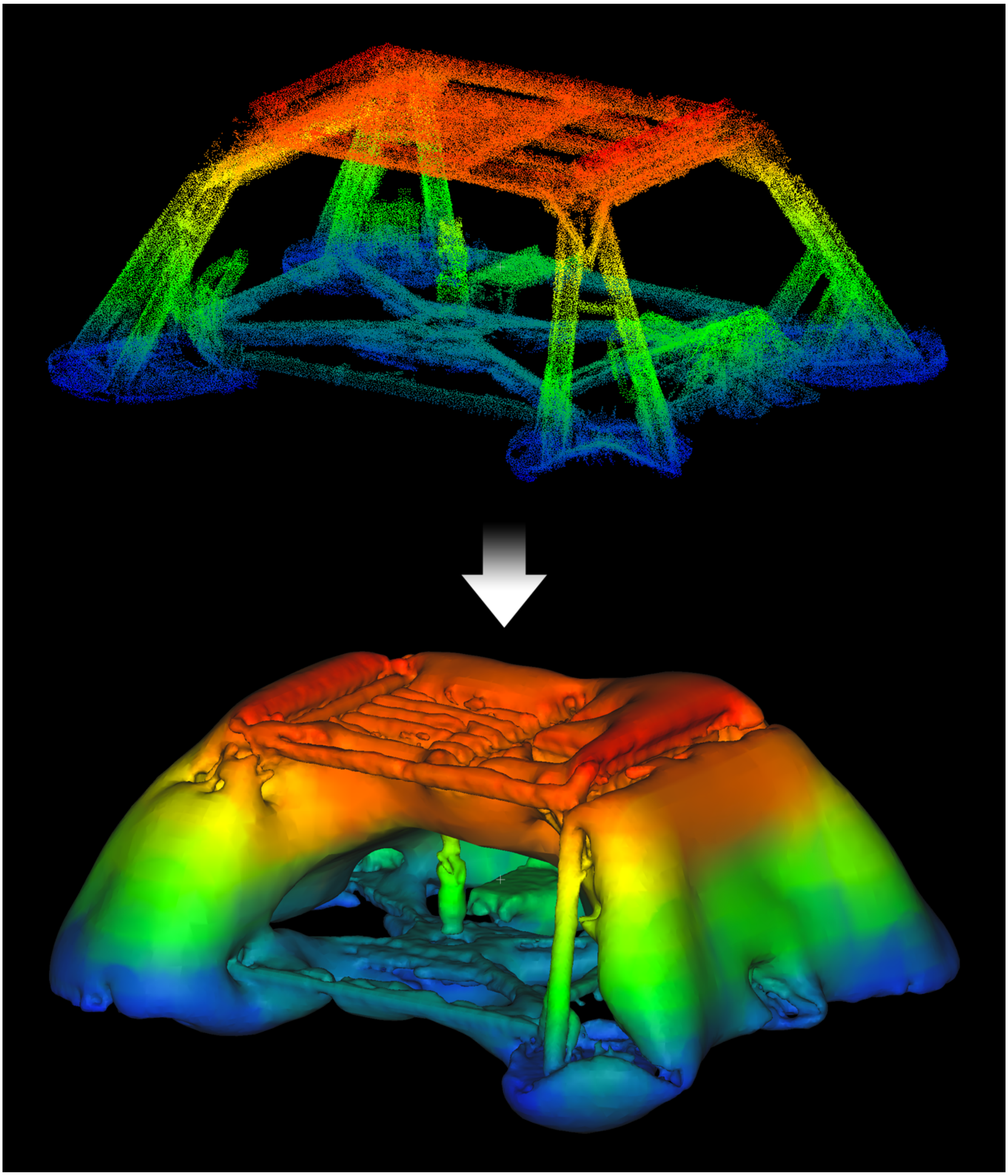

Figure 7.7: Image showing a point cloud version of the Troll dataset alongside the result of the automated surfacing techniques in CloudCompare

Unfortunately, the automated methods struggled to 'understand' the data and could not create adequate surfaces which represented the structure. An example of this is shown in Figure 7.7. Despite experimentation with a range of different software values and techniques, the complexity of the subsea survey data seemed to consistently confuse the software. When combined with the inaccuracy of some of the original points, the results of trying to automatically mesh the structure were unusable, mainly due to the software joining the wrong points together and not being able to find the edges between shapes correctly.

This was also likely due to the lack of 'surface normals' in the data. Surface normals are invisible vectors located at the centre of each polygonal surface plane, and define the direction in which each surface faces. It is important to note that point cloud data generated using sonar does not normally contain surface normals, or other types of facing information (the data is simply X, Y and Z co-ordinates per point). Surface normals are usually essential when texturing and lighting a 3D computer generated object, though they are equally as important when trying to automatically generate a surface model from a complex and/or confusing dataset. If each point in the dataset had a facing, the software would be able to construct a more accurate surface model, as it would better 'understand' how the points were placed and should be connected with one another. Also, due to the potential issues with the accuracy of subsea point cloud data, building an inaccurate surface model based on inaccurate data can only result in poor quality outcomes – where the margin of error multiplies each time something interpretative happens (loosely referring to the principle of 'garbage in, garbage out', which is often used in the field of computer sciences).

Due to the complexity of the Troll structure, it was quickly realised that these automatic meshing methods were not suitable. One solution would be to further the development of automatic meshing methods, though this type of task would sit outside the scope and focus of the author's own research which is primarily concerned with developing the visualisation and understanding of subsea survey data. As a result, the author was required to undertake the creation of a surface model of the Troll data manually.

Using the author's bespoke data loading tools,[53] the dataset was loaded into Autodesk Maya as a three-dimensional point cloud. Using this point cloud as a guide, the resulting surface model was then constructed using a series of 'primitive' shapes (such as cylinders or cubes), which were resized and scaled to fit each section of the point cloud data. As this was a manual process, additional care was taken to ensure that the primitive shapes fitted as closely and accurately as possible to the point cloud data they represented. During this stage of the workflow, reference was made to the original 'as built' plans and some video footage taken from a ROV, as a better, although still rough, indication of what the structure should look like.

If the automated meshing methods had been sophisticated enough to surface the Troll structure (or the structure had been less complex), this time-consuming manual work would not have been necessary. Using automated methods, a dataset can be surfaced in just minutes, whereas two full days of work were required to complete the Troll surface model manually. If this part of the process was quicker, it would save time and cost throughout a commercial process, and allow access to more advanced visualisation techniques, such as 3D printing, sooner.

Once surfacing was complete, a finished 3D model was exported in a generic file format ('OBJ' files contain simple 3D geometry) so that it was more accessible (and not tied exclusively to Autodesk Maya) – this OBJ file and the Maya project folder can be found in the accompanying data repository (Data 7.3). This finished model was then returned to the client as a completed outcome – where they could view, manipulate and measure the digital model in three-dimensions, giving them a clearer picture of the Troll structure as it was at the time of the survey.

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[53] This refers to the three *loadWreck* scripts introduced earlier, with full versions included in appendices 14.2.1, 14.2.2, and 14.2.3.

Data 7.3: Data repository > CS1 Troll > 03 Surface Model

Although completing the surface model fulfilled the requirements of the client's brief, it also enabled the author to undertake additional visualisation of the Troll structure and experiment with new ways of presenting the surface model or point cloud data, which could lead to improved understanding of which visualisation methods might prove to be more appropriate than others.

7.5.3 Using stereoscopy

One of the main issues with showing multi-dimensional data "has been how to represent three or more dimensions of data" on two-dimensional display surfaces such as computer screens (Tufte, 1997). Stereoscopy is a means of addressing this by presenting three-dimensional data using traditional two-dimensional displays.

Stereoscopy is a way of creating the illusion of depth and showing three-dimensional objects which appear to be 3D, by sending two different views to each eye separately. When combined, these allow the viewer to perceive the resulting image or animation in 3D. This is often controlled through the use of wearable glasses, though the way in which this is achieved varies – some systems use colour to separate the two 'eyes' (such as red/cyan, also called anaglyph stereoscopy), others might use 'active shutters' where the eyes are shown different images alternately in quick succession, leading to each eye seeing either the left or right images independently whilst the other eye is 'blocked'.

During the author's previous MSc work (Gauld, 2011) and research projects (De Sainte Croix et al., 2016; Macduff et al., 2014; Murray et al., 2013), the creation of stereoscopic outputs in Autodesk Maya had already been experimented with. This had previously been used to create simple 3D rotations of objects, using anaglyph stereoscopy, and had proven to be popular with those that had viewed it, bringing an extra feeling of realism and improving the clarity of the object being viewed. Because this process had already been tested, many of the implementation issues had been encountered and resolved, which allowed the Troll data to be converted into a stereoscopic format quickly.

As both point cloud and surface model versions of the Troll data were now available in Maya, the digital viewing camera was converted to a stereoscopic camera – a relatively simple update to the 3D work already completed, which would provide the left and right 'eyes' necessary for creating the illusion of depth. For the purpose of testing this process quickly, the surface model proved to be more useful than the basic point cloud – depth cueing was already much clearer with the Troll surface model, and it was hoped that the stereoscopy would continue to add to this clarity. An image showing a single completed anaglyph frame can be seen in Figure 4.12, though without the correct glasses this simply looks like a blurred or double image and seems to serve no purpose. It is only by using the appropriate red/cyan glasses that this truly becomes of interest, and the real effect is revealed.

Although the author's previous stereoscopic visualisation outputs proved to be useful and of additional value by showing clients' their data in new ways, there was no indication that the same approach to subsea survey data would also demonstrate this. Despite this method of visualisation adding a clearer indication of depth, and allowing 3D data to be viewed in an almost 3D way, a large amount of manual work was necessary in allowing point cloud data to be viewed using stereoscopy. It would be important to know if this investment was worthwhile or if there were other methods which may still give better results, perhaps with less time-investment or by providing increased visual clarity. A series of workshops were later conducted to review the different approaches to visualising the Troll data, and the stereoscopic version was included in this evaluation – this is discussed in greater detail in section 7.6, and provides some understanding to the differences or improvements between each technique.

In addition, now that a surface model of the Troll data was available, it allowed further experimentation with other types of visualisation, not just stereoscopy. Continuing the idea of finding better ways of viewing three-dimensional data, another potential solution to this problem would be through the use of 3D printing technologies.

7.5.4 Printing survey data

Additive manufacturing, more commonly known as 3D printing, is a way of creating solid physical objects from 3D digital files. Software is used to convert the digital object into a series of horizontal 'slices' which are then printed layer by layer, creating a physical version of the object.

After delivering the completed digital 3D files to the client, they opted to create their own 3D print of the Troll data. A comparison between the digital wireframe model and the physical 3D printed version can be seen in Figure 7.8. Although the creation of a digital surface model enabled the use of stereoscopy to 'add' to or enhance the 3D effect, a 3D printed model would be truly 3D. The client had undertaken this printing process to enable non-technical viewers to see, understand and easily interact with the Troll structure, and to also allow for measurements to be taken from the scale model.

This approach to measuring challenged pre-conceptions on the usage of such an object as it had been assumed that measurements would have been taken from the digital version of the structure, where the highest level of accuracy could have been achieved. Instead, measurements were taken manually from a 3D printed scale model, which could have introduced greater margins of error due to manufacturing processes in either the model or measuring equipment. However, it was discovered that measuring the 3D printed model was beneficial to those that were not technically literate or entirely comfortable using the complex software packages which would ordinarily be needed to make decisions based on the structure's condition.

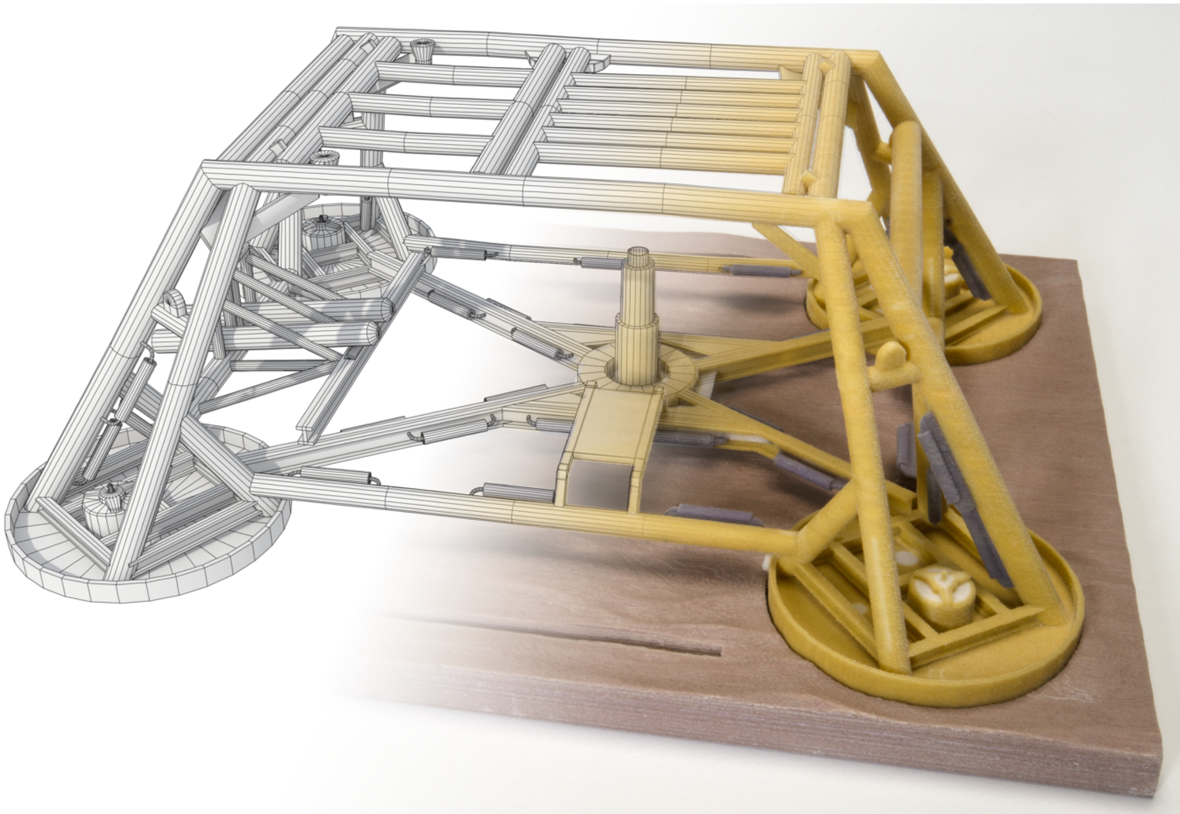

Figure 7.8: Comparison between digital wireframe model and physical 3D print, created using the same Troll dataset

This 3D printed version of the Troll data proved to be of great interest and encouraged further research and development, though at this stage the application of 3D printing was entirely new to the author. As the commercial client already had experience of 3D printing, they were able to transition from a digital file to a physical object relatively quickly. If the author were to understand this process better, it would create an opportunity for both ADUS DeepOcean and the 3DVisLab to develop and embrace another visualisation technique which could be applied to additional subsea structures.

Understanding the first steps of the 3D printing process was relatively straight-forward, as they had already been undertaken as part of the Troll work and could be reapplied to other datasets. Point cloud data would be imported to Autodesk Maya using the author's *loadWreck* data loading scripts, and then a surface model would need to be constructed. Alternatively, for simpler objects (such as seabed) this could be automatically meshed using CloudCompare.

Once a surface model had been created, the 3D geometry would need to be prepared for 3D printing, and this usually requires two additional steps to take place. The first of these is to ensure that the digital 3D object is a single 'closed' or 'watertight' object – that is, an object with no non-manifold or open edges. Having holes in the geometry can typically cause a file not to print at all, or to print a messy object which does not resemble the original file. Ensuring that an object is watertight before printing is easily done, as there are software packages which can check this automatically – and it is better to resolve it early than to try and 3D print a file which is not suitable.

The second step is to export the 3D file using the 'STL' file format (originally from STereoLithography), which is typically used by 3D printing software to communicate with and send files to the 3D printers. The 'OBJ' file format can also be used, though this is dependent on compatibility with 3D graphics packages and 3D printing software being used. The STL export step proved slightly more difficult to resolve as Maya does not natively support STL files. Initially, Rhino (an alternate 3D software package) was used as an intermediary to convert files, though a free plugin for Maya was later found which made this process both simpler and quicker.

With a surfaced object exported using the STL file format, it is ready to be 3D printed. Once the printing process is setup correctly, printing is as straight-forward as regular paper-based printing, though significantly more time-consuming.

7.5.5 Resolving print problems

However, as part of the author's work in testing and understanding the 3D printing workflow, it was not without its problems. These were encountered in the following areas: non-quad geometry, object scale, environmental conditions, and print bed temperature.

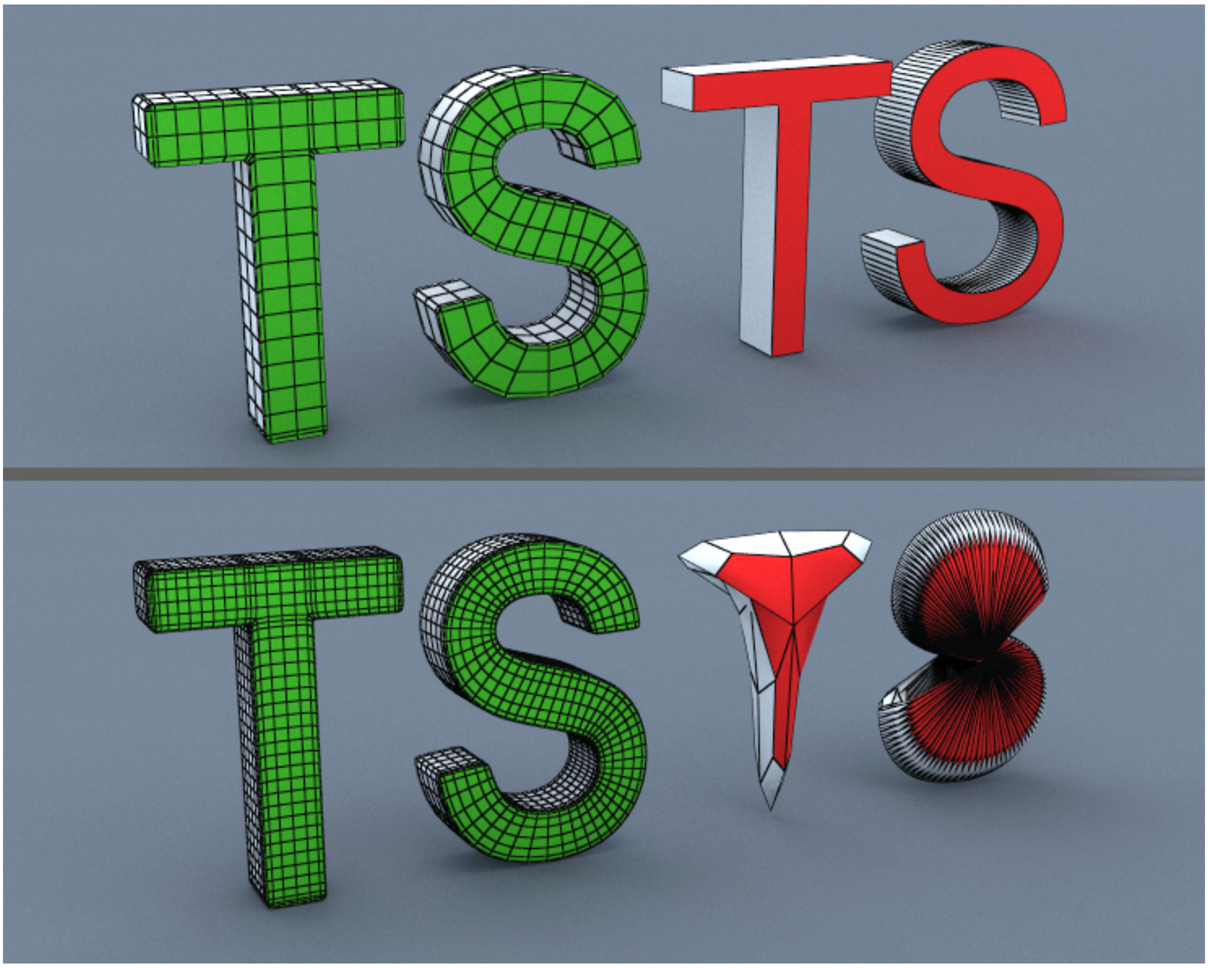

Figure 7.9: Non-quad polygons (or 'ngons'), shown in red, can subdivide unpredictably (TurboSquid, 2017)

One thing of particular note was the use of non-quad geometry. Typically, preferred 'good practice' in 3D modeling ensures that all of the polygons in a mesh are four-sided – this allows for easier subdivision or smoothing later (Figure 7.9), and can also help with object deformations through animation (TurboSquid, 2017).[54]

With 3D printing, both quad and non-quad geometry were tested, with no difference in the printed results. This was useful insight to gain, because sometimes maintaining clean quad-based meshes can be difficult and time consuming, though if this was not necessary (typically because survey data did not need to be animated or subdivided later), it meant that objects could be quickly joined together into a single watertight object using Boolean operations, whilst not being overly concerned with tidying up polygonal geometry.

On more than one occasion, a problem with object scale was encountered. Because of the 'real world' aspect of 3D printing, object size and scale are important factors to consider. There are many scenarios where the scale of a 3D printed object is irrelevant, and will typically be controlled only by creating the largest print possible (for example, an UP Plus 2 printer has a 'build volume' of 140x140x135mm). In these scenarios, users will often scale the size of their 3D model to fit the build volume limitations, with less regard for an exact scale ratio (often where the 3D printed model is not a miniature representation of another, larger object). Print duration and quality[55] also become an important consideration, as larger printed objects can take

[54] TurboSquid is a digital media company founded in 2000, selling stock 3D models to industries such as architecture and computer gaming. As of 2018, TurboSquid has over 679,000 3D models in its library, making it the largest library of 3D models for sale in the world.

[55] Similar to paper printing, 3D printers have different quality levels. For example, the UP Plus 2 3D printer offers three options on a continuum: fast (or draft), normal and fine.

significantly longer to complete – resulting in an increased wait, usually several hours, before the quality of the final object can be examined.

The size and scale of a 3D printed object can, however, become a critical factor, such as when preparing a reliable *scale model*[56] that can be measured and related to the original object which was modeled for 3D printing purposes. In these circumstances, it is essential that any software packages being used to prepare 3D models for printing have their units of measurement correctly aligned throughout.

Some of the author's early attempts at converting files for 3D printing were unsuccessful, resulting in prints that were sized incorrectly. Although the printing software allows for this to be corrected (by manually scaling the print size before printing, just as with scaling pages or images for paper printing), it identified a problem earlier in the software workflow which should be resolved – using Rhino as an intermediary step in the conversion process was scaling by a factor of 10, where the software interpreted millimetres as centimetres. On another occasion, a similar problem was encountered, though the model size was reported incorrectly by a factor of 2.54. Due to the value, this was found to be a conversion between imperial and metric, and again was a software setting which should have been checked earlier in the conversion process.

In addition to the software problems which were encountered, there were also issues with some of the 3D printed physical objects.

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[56] A version of something (such as a building or vehicle) which provides an accurate representation of the original, though at a different size. Often seen noted as a scale notation, such as 1:100, where the scale model is one hundredth the size of the original.

Figure 7.10: Print nozzle of an UP Plus 2 3D printer

One of the biggest potential problems encountered was managing the environmental conditions in which the 3D printing would take place. As the process involves heating plastic filament to high temperatures through a nozzle (shown in Figure 7.10 – this reaches 260°C when using an UP Plus 2 printer) and 'drawing' the object which then cools into a hardened state, inconsistency in room temperature can affect the way in which this happens – resulting in the object warping whilst still being printed. This was not a significant issue as part of this case study, as it had already been encountered by previous users of the DJCAD Make facility. As a result, the 3D printing equipment had been deliberately placed away from any windows and doors which could be opened, creating a more stable ambient printing temperature.

In addition, the importance of heating the print bed before printing was also considered. The print bed is a removable, flat panel which the 3D printing takes place upon (Figure 7.11). Without heating the print bed (which reaches 105°C with an UP Plus 2 Printer), the hot plastic filament is forced to cool much faster than is appropriate and causes the partially printed model to bend and warp away from its intended form.

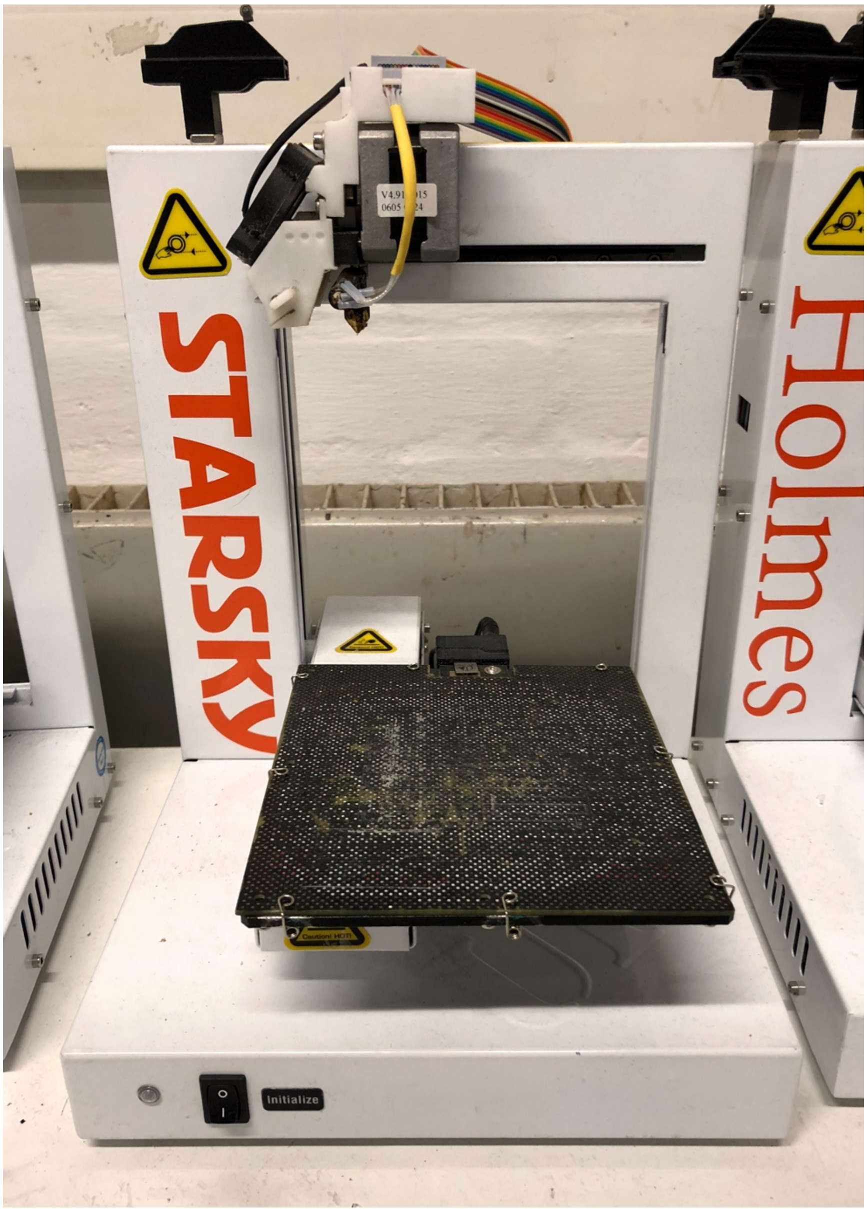

Figure 7.11: Print bed of an UP Plus 2 3D printer

For the best 3D printing results possible, an awareness of temperature is critical – both of the equipment and the surrounding environment. Adding this to a better understanding of how to prepare the digital models for printing allowed for the process to be streamlined, with potential issues being avoided so that an accurate 3D print could be achieved the first time, every time. Without this knowledge, it meant that several 3D printing attempts failed – and these were often over three hours in duration to complete, so a significant amount of time and troubleshooting could have been avoided.

7.5.6 Summary

As the author's involvement was on visualising the Troll data, the first task was to create a 3D surface model from the survey data. Initially, it was hoped that this could be completed using automatic meshing attempts, but it was quickly discovered that these are not yet sophisticated enough in understanding complex subsea survey data – often missing a high level of detail or accuracy, and without surface normals which can help with the automatic surfacing. Instead, the surface model was generated manually using more traditional 3D modeling techniques, which are time consuming but provide reliable results.

Once the surface model had been created, it enabled the data to be presented using three distinct methods – as a digital surface model, using stereoscopy, and 3D printing the structure. Using the Troll data to make each of these types of visualisation generated new knowledge in improving and streamlining the workflow of creating these, enabling them to be used as commercial solutions with minimal problems.

Finally, although the Troll data had unlocked potential in exploring different methods of presenting the data – mainly stereoscopy and 3D printing – further understanding was still required. To compare and evaluate how effectively these methods were able to present data, a series of workshops were conducted to test and validate the idea that these visualisation techniques could be worth the additional time and labour required in creating them.

7.6 Workshops

After extending the visualisation of the Troll E4E5 dataset, the author decided that it was important to better understand the evaluation of visual communication, and to also try and identify more effective ways of presenting data in both an engaging and stimulating way. This new understanding could ultimately lead to creating better visualisation outputs, resulting in the development of more useful ways of presenting, 'seeing', and interpreting data.

A short interactive workshop was developed where participants could review different methods of data visualisation, with the goal being to improve understanding of the communicative value that 3D visualisation techniques can add or remove when applied to subsea survey data. Ethical approval was applied for and awarded, and the application and confirmation letter are provided in appendix 14.3.

As part of this case study, the author chose to separate these evaluative workshops from the ongoing research practice. This was mainly due to the author's primary focus and expertise being on the practical elements and the creation of visualisation outputs. This was undertaken with the understanding that any evaluation of practice is still vital, and should be explored independently as methods may differ, and it would be unfair to approach all aspects of research in the same way (Brewer and Hunter, 2006).

7.6.1 Methodology

Structured using the author's **Explore Review Create** methodology, the creation and delivery of this workshop was undertaken using a multi-method approach. A design research approach was maintained, encouraging practice-led learning and development. With action research proving similar to design research, (McKernan, 1996) the application of each of these resulted in a cyclic or iterative process of self-improvement.

With the author also adopting the role of the reflective practitioner (Schön, 1991), this continued iteration was supported by encouraging reflection and improvement during all stages of the research processes, rather than just an analysis or evaluation of a finished product or experiment. In this case, the workshop and its outcomes created more opportunities for knowledge and learning to be extracted and then applied, improving both the process and the product.

7.6.2 Aims

This workshop was created with the aim of investigating three specific questions:

- Can the use of visualisation techniques improve our understanding of the underlying data?
- At what point during the visualisation process does this happen?
- Can 'over-visualising' remove this new level of understanding?[57]

The workshop was also intended to capture both quantitative and qualitative (multi-dimensional) data. Analysis of this resulting data proved useful in determining the visual value, if any, that was added to or removed from the data by using different methods of presenting a series of visualisation techniques, all built from a single dataset.

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[57] 'Over-visualising' refers to undertaking additional and perhaps unnecessary steps with no worthwhile improvement to visualisation results.

7.6.3 Locations

This workshop was hosted four times, each with a slightly different audience, detailed below:

- Small Society Lab (June 2014) – a range of academics and researchers, with mixed experience of 3D computer graphics.
- Edinburgh Napier University (October 2014) – digital media students, who have studied 3D computer graphics and animation techniques.
- Mozilla Festival (October 2014) – a wide variety of (mostly unknown) participants, likely to include designers, researchers, technologists and members of the public.
- Fife Council (January 2015) – a group of professionals with little-to-no knowledge of 3D computer graphics, visualisation or subsea survey data.

The Mozilla Festival data was later removed, as the results were shown to be largely influenced by the lack of an available 3D printed model (one of the key research areas of interest), which was due to restrictions in the event space provided. The results from the other three workshops were later combined, though the original individual workshop results were also retained.

7.6.4 Participation

Participants were presented with eight key stages of visualisation development, shown in Figure 7.12 through Figure 7.19, starting with the raw numerical data (as captured by multi-beam sonar) and ending with a physical 3D print of the structure. The same Troll dataset was used throughout.

These eight stages were chosen as they gave enough differentiation and clarity between each of the stages, though with not so many minor differences that it would be difficult to follow, particularly for participants who might be considered non-experts in visualisation techniques or understanding subsea survey data.

Stages one through four represent the typical steps that result in the deliverables that ADUS DeepOcean would generally provide a client. In order: raw numerical data, point cloud data, processed (cleaned and subsampled) point cloud data, and interactive 3D point cloud (presented in ADUS DeepOcean's own WreckSight visualisation application).

Stages five through eight show further development beyond the current deliverables: surface model, rendered surface model, anaglyph stereoscopy, and 3D printed physical model.

Figure 7.12: First of eight stages of visualisation development as used during the Troll workshops (raw numerical data)

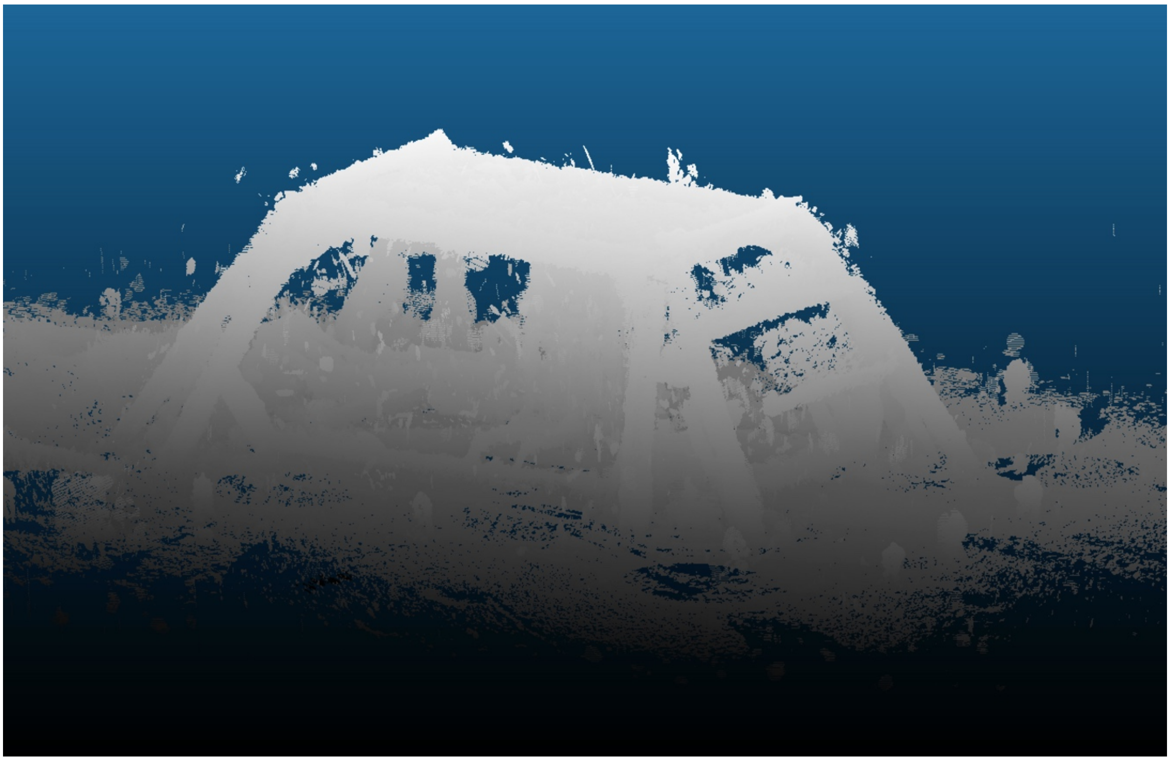

Figure 7.13: Second of eight stages of visualisation development as used during the Troll workshops (point cloud data)

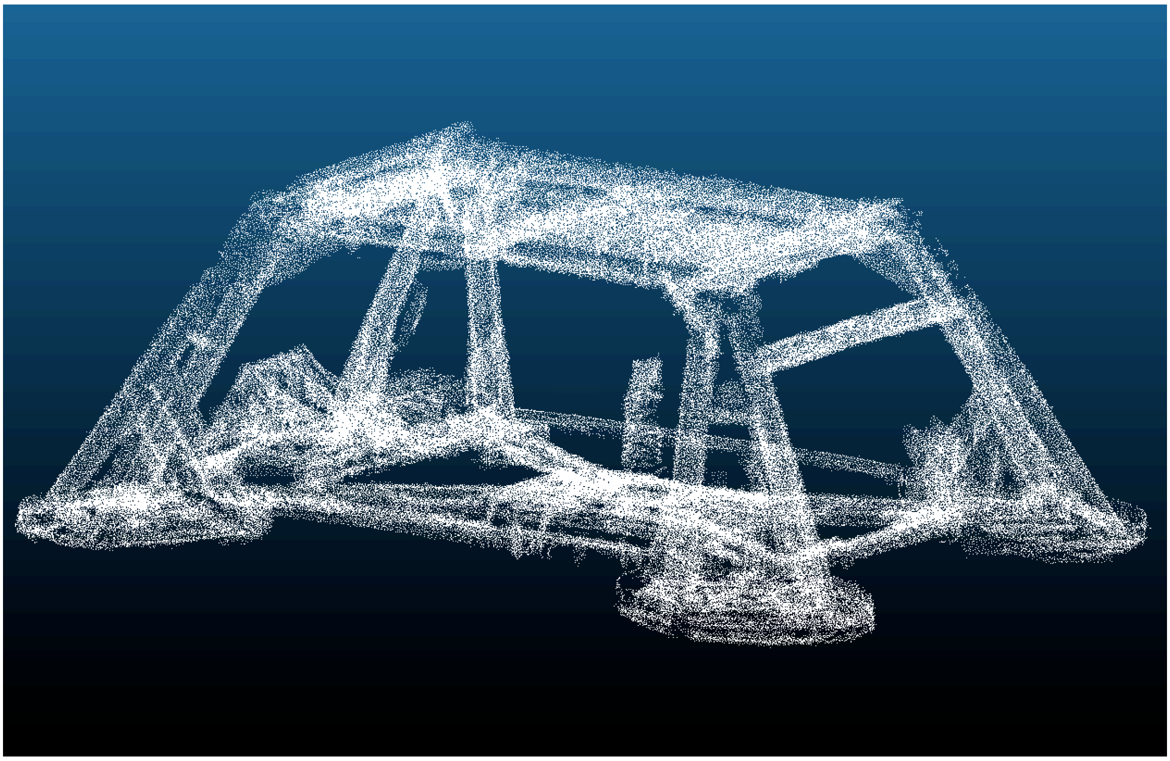

Figure 7.14: Third of eight stages of visualisation development as used during the Troll workshops (processed point cloud data)

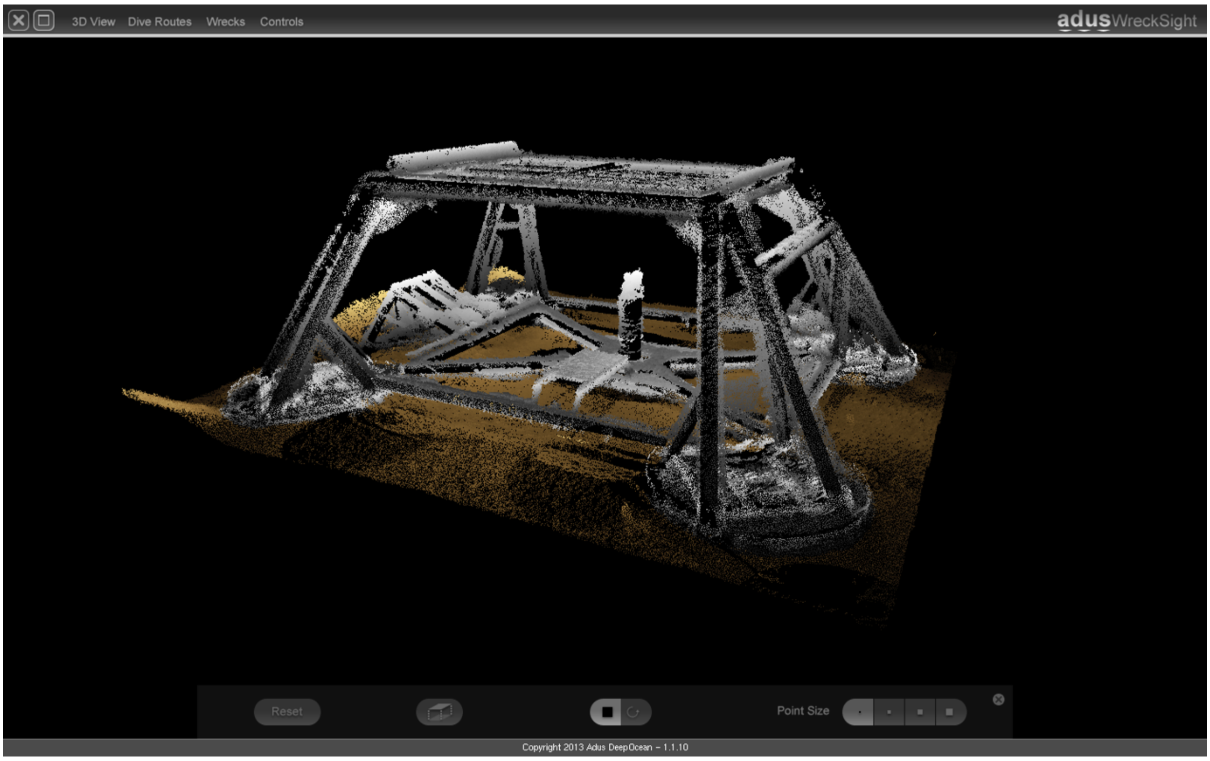

Figure 7.15: Fourth of eight stages of visualisation development as used during the Troll workshops (WreckSight – interactive 3D point cloud)

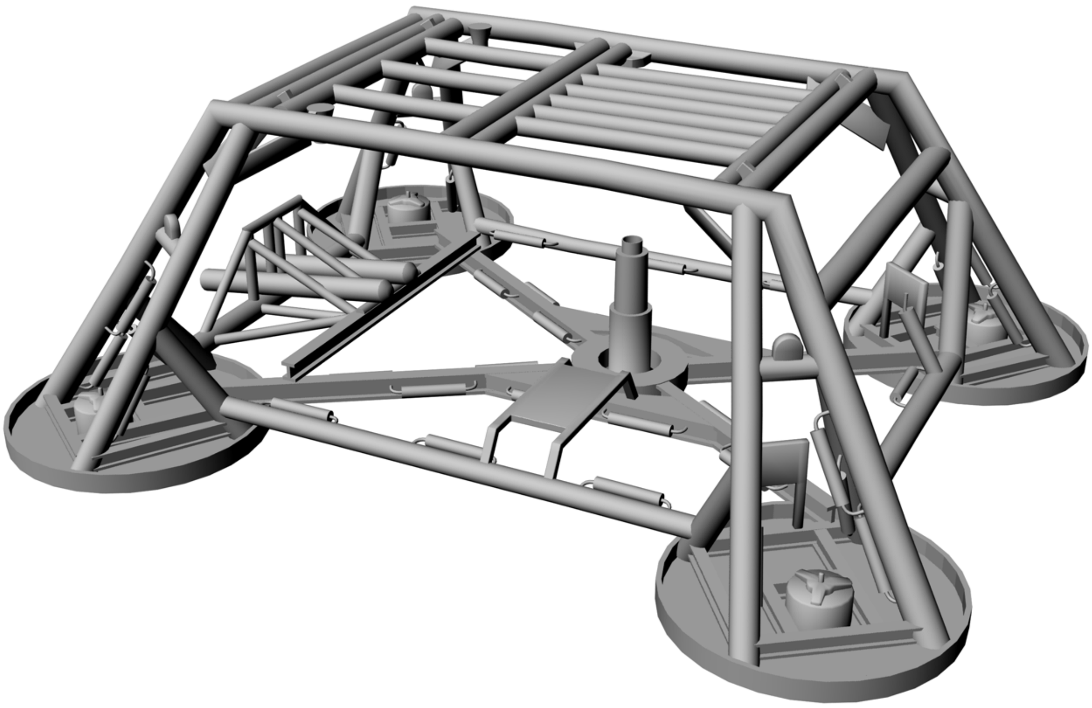

Figure 7.16: Fifth of eight stages of visualisation development as used during the Troll workshops (surface model)

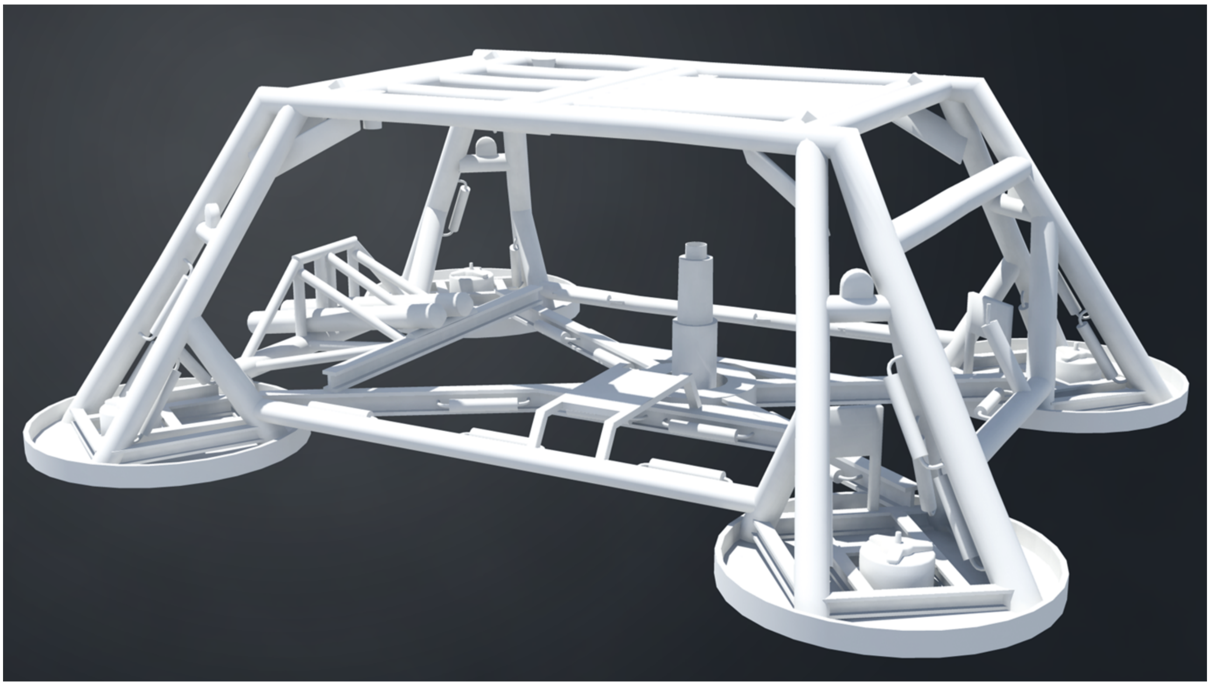

Figure 7.17: Sixth of eight stages of visualisation development as used during the Troll workshops (rendered surface model)

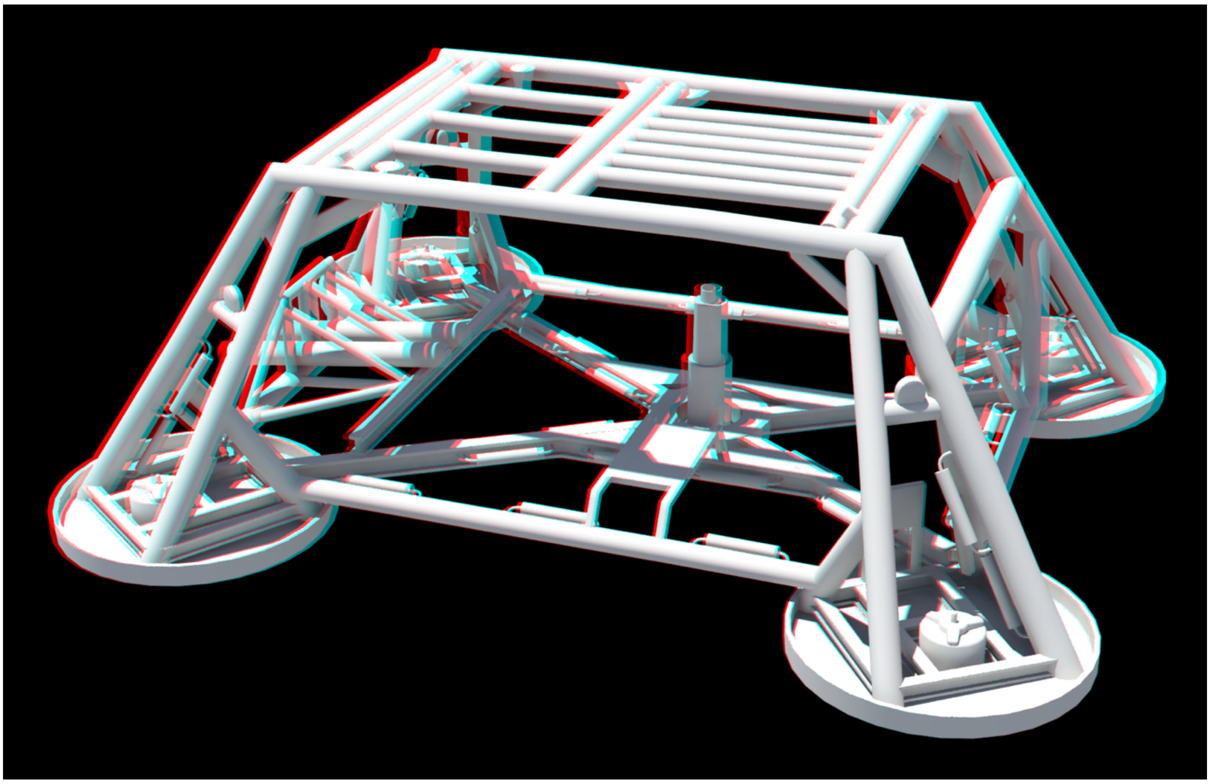

Figure 7.18: Seventh of eight stages of visualisation development as used during the Troll workshops (anaglyph stereoscopy)

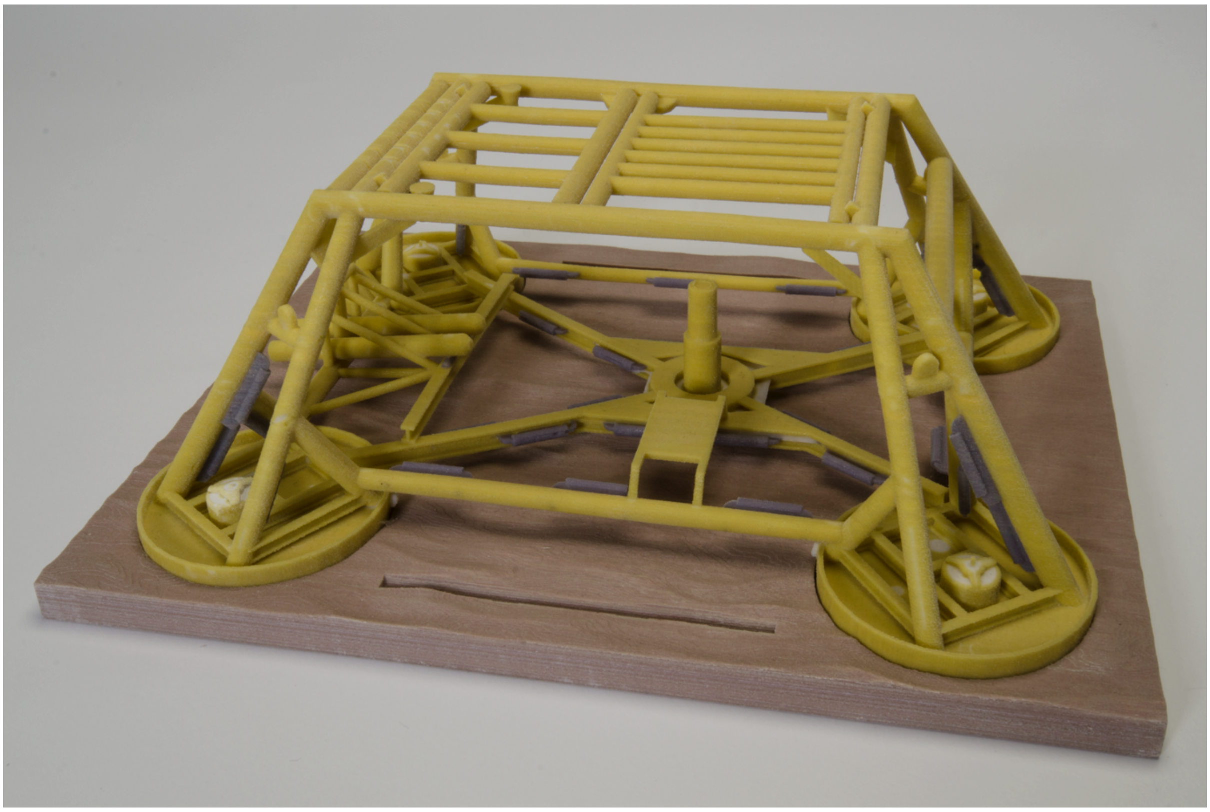

Figure 7.19: Eighth of eight stages of visualisation development as used during the Troll workshops (3D printed physical model)

It is important to note that for stage seven, suitable glasses were provided for viewing, and for stage eight, the 3D print was present throughout the process (unfortunately, it was not present during the Mozilla Festival workshop).

Once the most important stages in the data visualisation lifecycle had been identified and prepared, a grading system was developed. This had to be simple for participants to use, but still allow for easy gathering of the results in a clear and efficient format.

Initially, a 'traffic lights' system – where a user would place a red, amber or green sticker to show their level of understanding of a particular visualisation stage – proved to be too simplistic in capturing opinions. Numerical rating of each image (e.g. from 1-10) offered a more precise measurement of understanding, but did not offer the ability to capture the thoughts and opinions behind decisions either.

As a solution, participants were asked to place a sticky note by each image as their 'vote' along a spectrum of options (providing quantitative data for direct comparison of methods), and could also write any thoughts that they may have had onto the sticky note (providing qualitative data for deeper analysis). The grading categories for each visualisation stage can be seen in Figure 7.20.

Figure 7.20: Grading categories for stages during Troll workshop

Before placing any sticky notes, participants were briefed on what each of these visualisation stages represented, and Figure 7.21 is an example taken from one of these completed workshops, showing both the grading scale and the way in which participants provided their responses.

Interestingly, some of the workshop participants wanted to know more about the grading scale rather than the visualisations. The subjectivity of such headings was questioned, though this also highlighted a similarity between the interpretation of these workshop headings and the current ways in which data is evaluated, which is often on an individual or personal basis – we all have different ideas of what 'better' or more 'exciting' data is. In the case of the workshop headings, these were chosen by the author as more natural 'human' responses to visualisation, rather than disengaged and numerical choices.

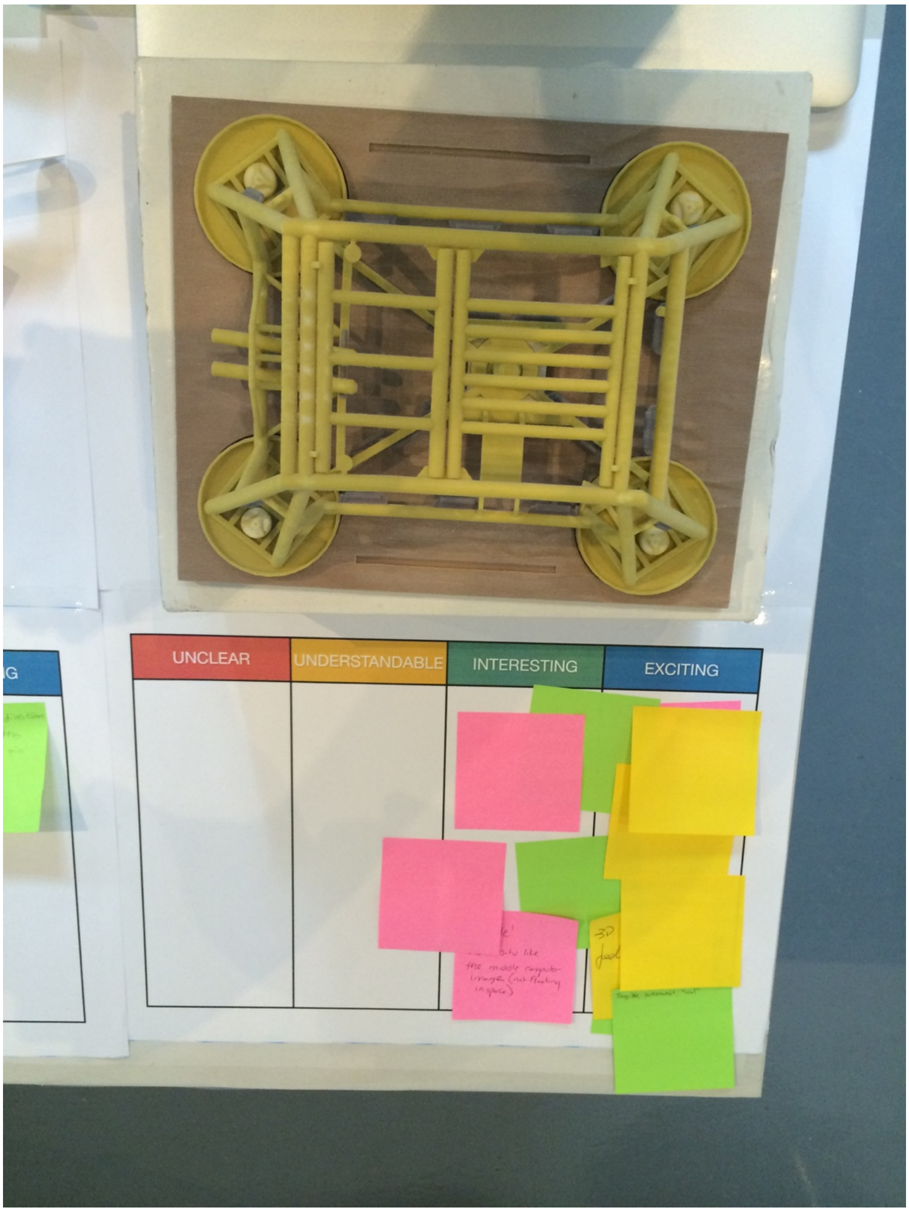

Figure 7.21: Example of Troll workshop outputs

7.6.5 Responses

After compiling all of the participant's responses from each of these three workshops, some reflection and analysis was completed, based on the resulting data that had been gathered, collated and visualised – shown in Figure 7.22.

If we first consider the number of responses (around 40 participants in total), not all of the visualisation stages received an equal number of votes, suggesting that participants either voted for some twice, or chose not to grade particular stages – making it difficult to know exactly how many participants there really were.

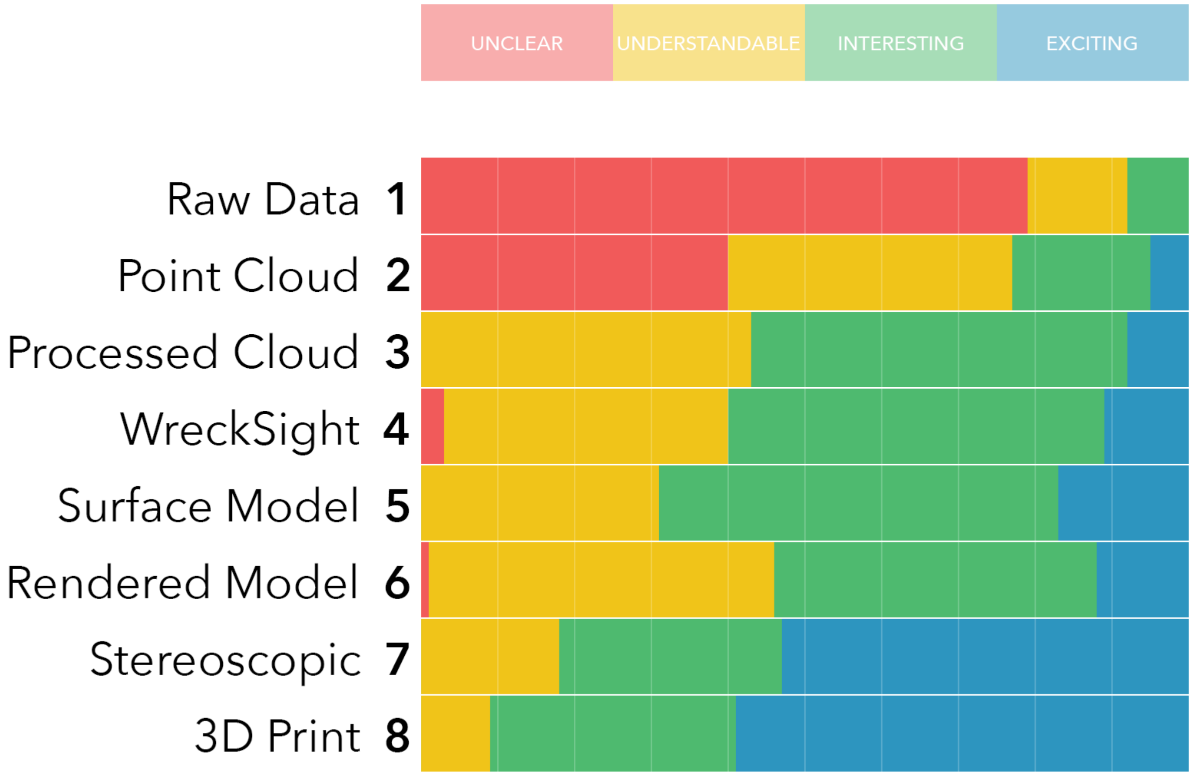

Figure 7.22: Compiled responses from Troll workshops

Of particular interest is that stages five and six received around 5% less votes than the average, and stages seven and eight received approximately 5% more than the average number of votes. This could imply that people were perhaps drawn to these images in particular, as during the workshops, the creation of surface models seemed to be of less interest than the use of stereoscopic or 3D printing as visualisation methods.

Upon transitioning from stage one to two, more than half of the participants found the same dataset understandable. A noticeable increase in understanding the data was achieved by stage three, where the data had undergone some processing and cleaning, with all of the participants acknowledging a basic understanding. There is no further notable increase in basic understanding levels beyond this stage of visualisation.

However, combined levels of interest and excitement generated by the varying presentations of data appear to have increased gradually throughout each of the stages, though stage six shows a decline, which suggests that this visualisation stage should be absorbed into the others as it has no importance of its own.

Combined levels of interest and excitement continue to climb during stages seven and eight, suggesting that although basic understanding is not increased using these emerging visualisation methods, both interest and excitement are – this could lead to greater engagement with survey data, and an increased amount of discussion around the dataset, as was evident during the course of these workshops.

Additional visual exploration of the participants response data was undertaken, with all of the results mapped into histogram format showing the distribution of responses. These histograms can be seen in Figure 7.23. Following the development of the visualisation techniques (from left to right), it showed that the most common response on each visualisation technique also progressed from *Understandable* (red) to *Exciting* (blue).

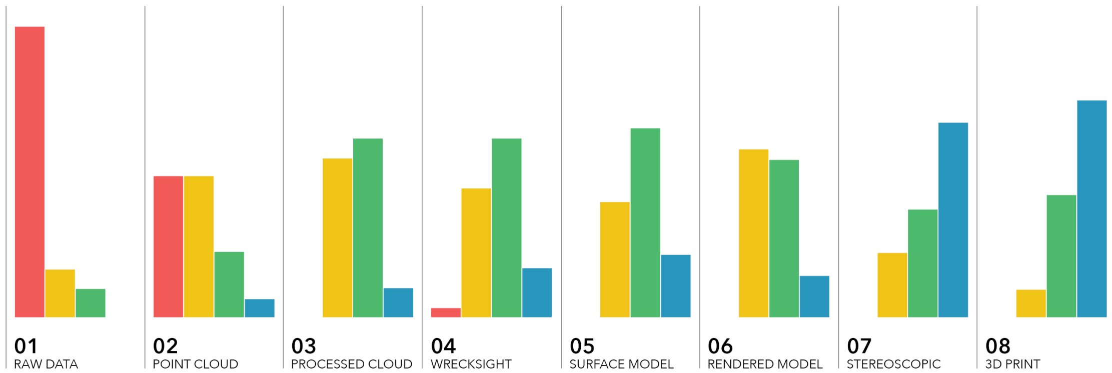

Figure 7.23: Histograms showing compiled Troll workshop responses

Reviewing the qualitative participant responses allowed for greater insight into how the participants perceived the visualisation stages. A summary of some of these responses can be seen in Table 7.1, which shows typical comments from a selection of participants on each of the eight stages used during the workshops.

Raw data (1)	"Very unclear and difficult to understand"	"No clue what this is"
Point cloud (2)	"A complete mess but you can see basic structure"	"Not clear but easier to understand than a list of numbers"
Processed cloud (3)	"Better idea of what the visualisation looks like, but no sense of depth"	"Structural data much clearer"
WreckSight (4)	"Interesting looking, visible structure and good for use with measurements"	"Visually interesting but not completely understandable without deeper context"
Surface model (5)	"Increased sense of substance"	"Clean model but wouldn't show potential decay"
Rendered model (6)	"Understandable, however no more exciting or thought provoking than previous visualisation"	"Doesn't feel like a valuable progression from previous step"
Stereoscopic (7)	"Improves visual interest. More engaging"	"Very clear and stereo adds extra dimension"
3D print (8)	"Tangible, substantial, 'real'"	"Ultimate visualisation which allows you to feel, see and touch a scale version of underwater structures"

Table 7.1: User responses gathered from Troll workshops

As expected, the comments received on each of these stages generally matched with the quantitative workshop data results – showing lack of understanding at the start, which gradually improved throughout.

As with any workshop of this type, there were occasional comments that were completely different to what was expected – one participant had said they found stage one (showing raw numerical data) the most interesting because it looked like rivers of numbers.

7.6.6 Analysis

In addition to reviewing all of the data gathered at each of the workshop events, some statistical analysis was also completed afterwards. This was undertaken with input from a statistician and using the software RStudio – an open-source user interface for the powerful statistical computing software environment R.

So that the statistical analysis could be completed, user responses were mapped as "Scores" to values 1-4 (with 1 representing 'Understandable" through to 4 being "Exciting"). So that there was no confusion between two sets of numbered items, the eight "Presentation" stages were labelled A-H, in the same order as previously seen.

Due to the type of data being analysed, it was suggested that a non-parametric Kruskal-Wallace test would be most suitable. This allows for one nominal variable and one ranked variable to be tested. RStudio provided the results of the analysis, which were shown to be highly significant with a *p-value* of <0.001 (less than one in a thousand chance of being wrong). With such a result, it can be concluded that the pattern of responses is highly unlikely to have occurred by chance.

7.6.7 Summary

Finally, returning to the original workshop questions will show whether these were answered or not. These three questions were:

- Can the use of visualisation techniques improve our understanding of the underlying data?
- At what point during the visualisation process does this happen?
- Can 'over-visualising' remove this new level of understanding?

The first question refers to the use of visualisation techniques as a means of improving our understanding of the data they represent. In the case of the Troll data and the various presentations, the results of the workshops show that the amount of ‘unclear’ responses was reduced, showing that the level of understanding did improve throughout, particularly during the early stages – which provides an answer to the second question. It also confirms that the current approach to visualisation of subsea survey data is worthwhile and adds to the data being presented.

With the exception of stage six (showing a rendered surface model), each of the stages also showed not only a marked improvement in understanding, but also gradually becoming more interesting and exciting as new presentation techniques were introduced, again providing a better answer to the second question. This suggests that this use of new techniques of visualising subsea survey data could be of greater importance – for example, both stereoscopy and 3D printing offer the ability to view 3D data using all three dimensions, which intuitively feels like a benefit over 2D visualisation techniques. This begins to provide an answer to the third question, as with the exception of stage six (which could easily be removed from the working process if it is unnecessary), there was no noticeable ‘over-visualisation’ which proved to be negative in terms of appeal or understanding.

Based on the responses from the participants and statistical analysis of data, the use of visualisation methods beyond those already commonly used could have some value in communicating data more clearly. At this stage, it is difficult to pinpoint exactly why one presentation type may be more useful than other methods however, and this is something that should be explored further.

7.7 Findings and reflection

The Troll dataset proved to be of great value as a case study. Despite initial problems during acquisition and processing – which were resolved by ADUS DeepOcean and the 3DVisLab – the data was of a high enough quality to allow for experimentation with new visualisation techniques beyond those which the industry is presently using.

In doing so, the Troll dataset created an opportunity to directly compare visualisation techniques – both current and experimental. As discovered during the Troll workshops (section 7.6), those techniques which offered a three-dimensional view of three-dimensional data were seen as more successful, with stereoscopy and 3D printing in particular showing noticeably more interest and appeal than other means of presenting the Troll data.

In creating these different means of visualising the Troll data, the creative practice (section 7.5) offered a unique opportunity to work with complex subsea survey data, and allowed the author to understand and resolve any technical issues encountered during the visualisation process. This new knowledge and understanding can then be applied commercially. For example, if a client were to request that their data deliverables be suitable for 3D printing, this could be completed in a timely and problem-free manner.

However, during the author's involvement with the Troll project and data, it became apparent that being new to subsea survey data was an issue, and a greater understanding of the acquisition and processing of this type of data would be essential. A researcher or practitioner who understands the whole process has a better awareness of potential problems which may be encountered throughout and how they can be avoided, rather than responding to them after they cannot be resolved or when it becomes challenging, time-consuming and resource-intensive to do so.

7.8 Future work

Throughout the Troll case study, two main opportunities to develop the work beyond the original research were identified.

The first, and most significant of these was in highlighting any issues in which subsea data is acquired and processed. Although in this instance, some of these were resolved before the author's involvement, improved knowledge of these stages of the process is essential, and contributes to a better understanding of survey data and creating stronger visualisation results. To address this issue, the author undertook a commercial placement with ADUS DeepOcean which involved acquisition and processing of subsea data, forming the basis of the Gabbard case study (chapter 8).

As the second of these opportunities for future work, the Troll practice and workshops evaluated different visualisation techniques against one another, using the same source of data. However, as there was only one source of data available during the workshop design, the workshops focussed on evaluating different visualisation techniques created using this single dataset. The workshops were not able to consider a comparison between two different datasets using the same visualisation technique – one which was captured poorly against one which was captured well, and measuring the difference this might make to the visualisation process and outcomes. To better understand the differences that data quality makes to a single visualisation output, the fairest comparison would be using two datasets gathered in the same conditions and capturing the same subsea structure. In practical terms, this would compare a specialist high-resolution Troll dataset to the existing lower-quality Troll dataset, where other variables have been reduced or removed. Unfortunately, due to the significant expense involved in undertaking any type of subsea survey[58], further data acquisition was not possible as part of the case studies that were dependant on commercial datasets being made available for research purposes. Although it is generally assumed that having stronger data will lead to

[58] Though the figures can vary greatly from project to project, costs can regularly be measured in tens of thousands of pounds. Companies are hesitant to publish these types of costs, so exact figures are not provided. Figures typically include vessel and equipment hire, contractor wages, and subsistence expenses.

stronger visualisation, the provided Troll data did not offer the opportunity to validate this theory, and so this is something that should be considered in future studies, where data acquisition may be more flexible.

8 Case Study 2 – Gabbard

This second case study focuses on the visualisation of subsea assets for ADUS DeepOcean at the Greater Gabbard wind farm site. The author worked with ADUS DeepOcean for a period of approximately 3 months (starting July 2014), as part of a large-scale surveying project on behalf of their client, SSE (formerly Scottish and Southern Energy). ADUS DeepOcean were commissioned to survey the offshore wind farm at Greater Gabbard as part of a longitudinal study, and this was the first on-site survey undertaken.

The following sections will introduce the site location and why it was surveyed, followed by an exploration of the practice, reflection and findings of the author as part of this case study.

8.1 Greater Gabbard

Greater Gabbard is an offshore wind farm, located in the North Sea, 25km off the coast of Suffolk (shown in Figure 8.1). After 10 years of planning and construction, it was officially opened in 2013, and contains 140 wind turbines, “providing enough renewable energy to supply around 530,000 homes each year” (SSE, no date). It has also provided a significant boost to jobs and commerce in the region, as SSE continues to develop a local supply chain and source employees from the surrounding area.

Each of the Gabbard turbines are 131m in height, and are located at depths ranging from 20 to 32m. These turbines are joined using a series of buried subsea cables, with a total of 175km in length of connecting cables being used. Generated power is collected in offshore stations, and brought onshore using three 45km export cables.

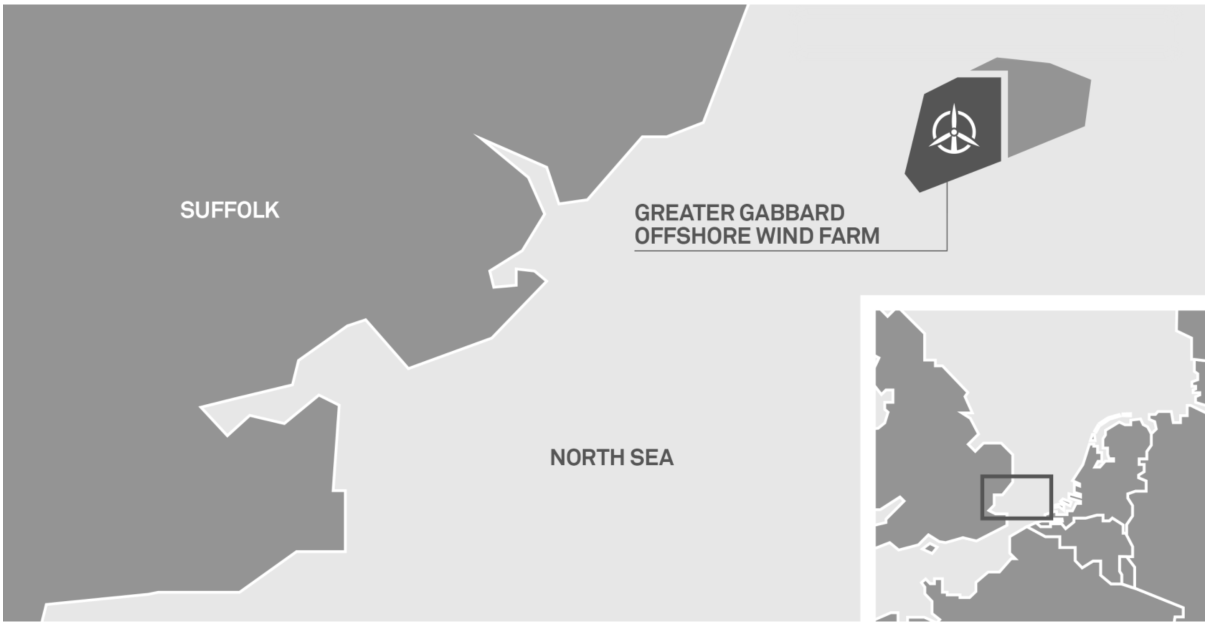

Figure 8.1: Location of Greater Gabbard (SSE, no date)

Figure 8.2: Offshore wind turbines, part of Greater Gabbard (SSE, no date)

As part of ongoing asset maintenance, the client brief required the undertaking of a series of geophysical surveys which would be used to inform and monitor three primary elements:

- Condition of the underwater assets (turbine foundations and cables).
- State of the seabed, and identification of seabed debris.
- Identification of scour or sediment accretion within the whole of the wind farm area.

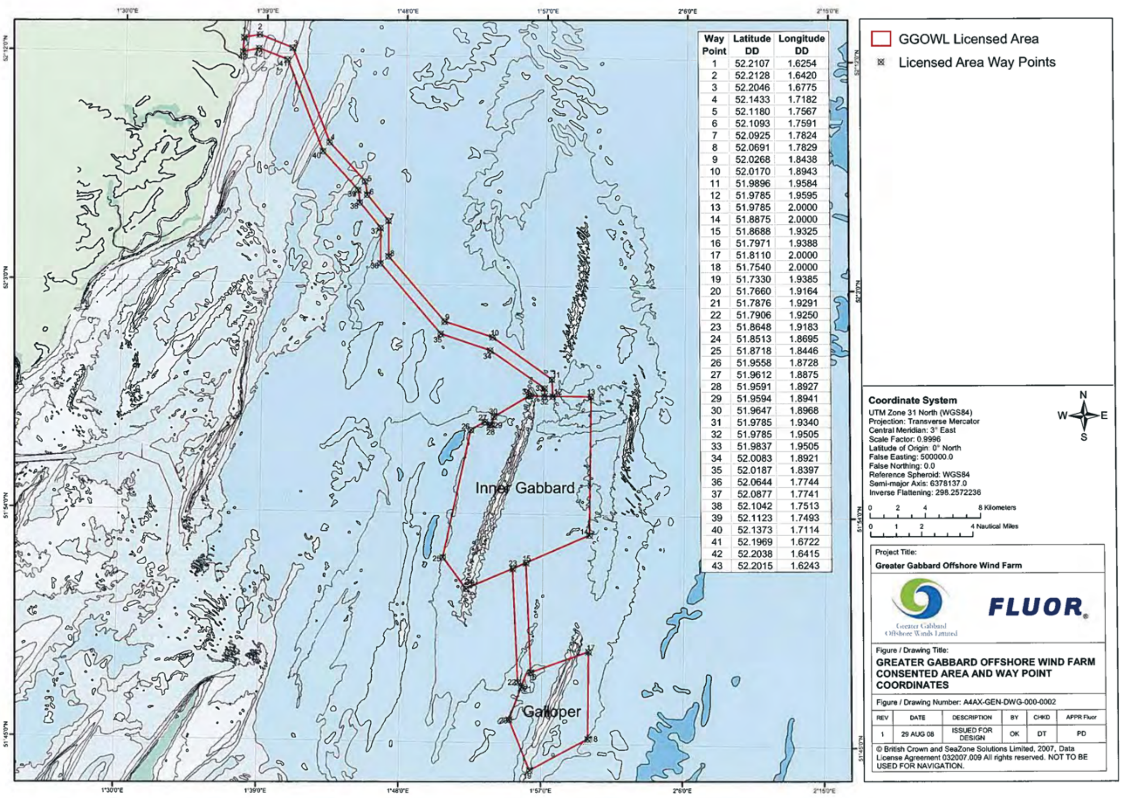

Figure 8.3: Image showing layout and licensed area of the Greater Gabbard offshore wind farm (SSE, no date)

Rather than use subsea divers to inspect assets and record findings, which is time consuming and potentially dangerous, the project would be completed using multi-beam sonar. This would involve acquiring survey data of each of the 140 wind turbines, and of all the cable 'corridors' linking them together, ranging from 800 to 5200m in length. The turbines themselves were split into two smaller sites (shown in

Figure 8.3), spanning a total area of approximately 146 km^2, though not all of this would fall within the scope of the survey. A more detailed view of each of these sites is shown in Figure 8.4.

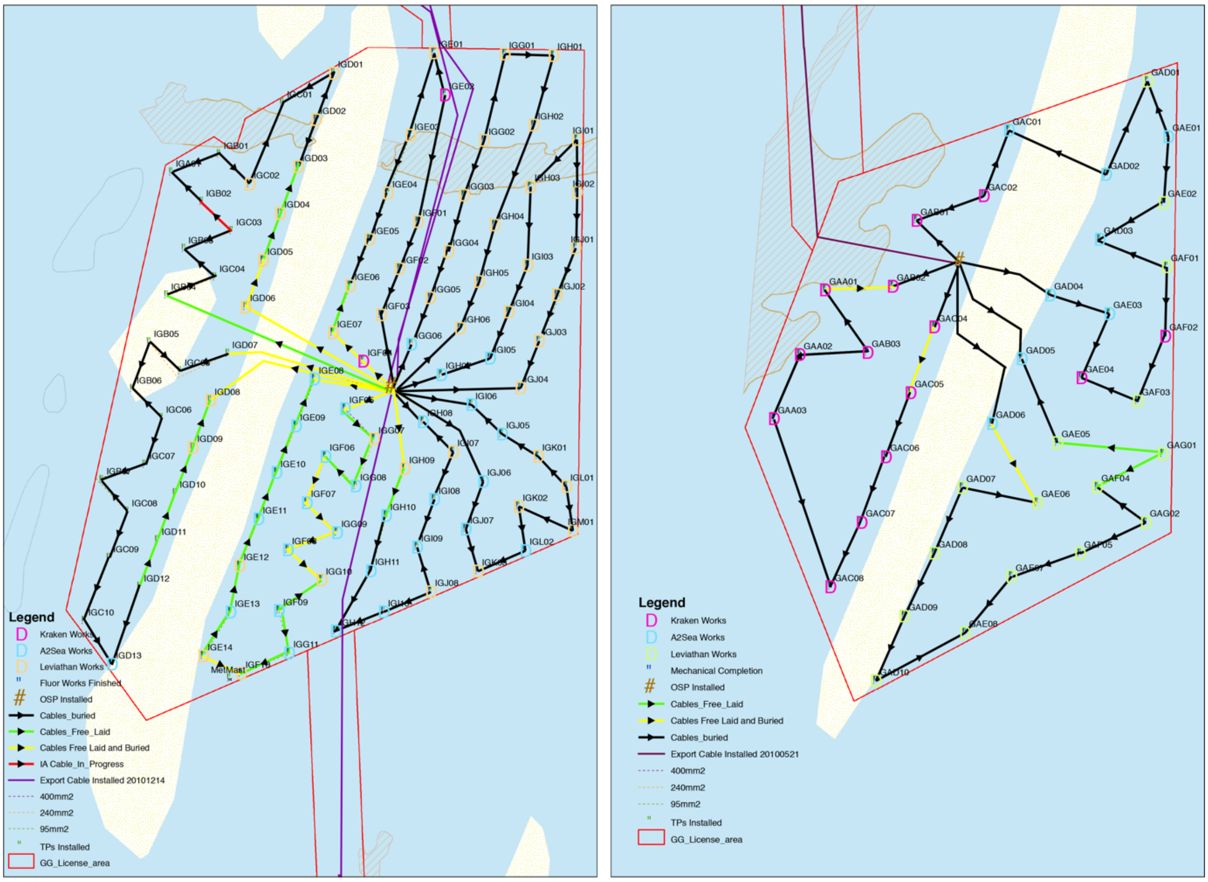

Figure 8.4: Map detail showing Inner Gabbard (left) and sister wind farm Galloper (right) (images provided by ADUS DeepOcean)

As part of ADUS DeepOcean's involvement in undertaking this work, high resolution data would be acquired and presented in an interactive 3D format. This would create a detailed snapshot of the status of SSE's assets and of the surrounding seabed (within the immediate area, typically 100 metres in each direction). This would also provide data which would facilitate the monitoring of changes over time – providing valuable information for ongoing maintenance and repair planning and procedures.

Based on the brief and further discussions with the client, ADUS DeepOcean's survey objectives were as follows:

- Undertake high resolution subsea quantitative imaging of the turbine foundations and cable runs.
- Identify seabed debris within the construction area.
- Identify changes to seabed morphology to enable the evaluation of the effectiveness of installed scour protection and ratify the predictions for scour development.
- Inform the foundation and cable maintenance schedule.
- Satisfy the requirements of the Marine Licence.[59]

Upon completion of the subsea surveys, ADUS DeepOcean were required to deliver a series of assets in GIS format, alongside imagery and profile data of the turbine foundations (these were provided in a printable 2D image-based format, though could also have been supplied in an interactive 3D format if required). A series of field reports would also be submitted containing daily logs, summaries of work completed, calibration reports and preliminary results.

8.1.1 Industry collaboration with ADUS DeepOcean

ADUS DeepOcean originally specialised in the high-resolution multibeam sonar survey of shipwrecks, and has developed unique 3D interactive visualisation technology which can be applied to different types of survey data.

More recently, ADUS DeepOcean activities have expanded to include surveying a variety of other man-made structures that require very detailed investigation or monitoring, such as offshore wind turbines and sub-stations.

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[59] The Marine Management Organisation (MMO) is responsible for marine licensing, existing to make a contribution to sustainable development in the marine area. The MMO covers licensable activities such as dredging, removal of any substance or object, or scuttling of any vessel or floating container.

Prior to starting the Gabbard project, ADUS DeepOcean had undertaken a number of trial surveys on a windfarm off the UK coast, employing their surveying expertise to offer a state of the art approach to the management of these types of assets. For the client, SSE, this experience could offer a more cost-effective approach to many operational and maintenance procedures, as well as documenting the current status of assets for those responsible for their management.

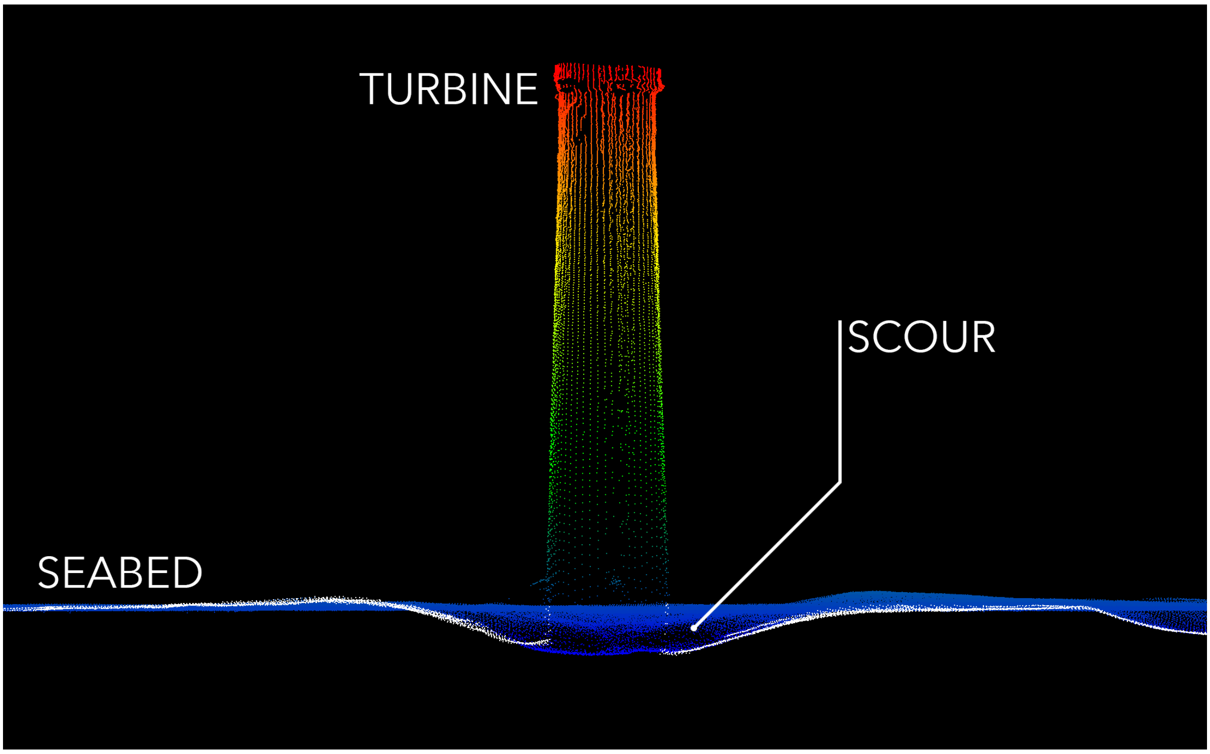

Figure 8.5: Profile image taken from sonar data, showing an area of scour around the base of an offshore wind turbine

ADUS DeepOcean have extensive experience of very high resolution multibeam sonar surveying of man-made structures situated on the seabed, including wind turbines and their interconnecting cables. This experience also includes visualising the data in a unique way which allows problems associated with scouring or sand-wave migration to be quantified (Figure 8.5).

ADUS DeepOcean have also worked in collaboration with the 3DVisLab at the University of Dundee since 2006, developing new methodologies for both collecting and presenting subsea survey data, which allows for a specialist approach to a large-scale project as undertaken on behalf of SSE.

8.1.2 Collaboration with 3DVisLab

As part of the Gabbard case study, the author was working with ADUS DeepOcean primarily in the acquisition and processing of the wind-farm survey data. Collaboration with the 3DVisLab was minimal, as their involvement was in visualising the data (using their proprietary visualisation software) after it had been processed by the author as part of the ADUS DeepOcean project team.

8.2 Research questions

With the research questions continuing to drive the overall direction of research, they will be revisited below, and their relevance throughout the Gabbard case study considered.

> **RQ0:** Can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?

After the completion of the Troll case study, it was revealed that in order to create the best quality visualisation outputs, care should also be taken when acquiring and processing the data. As part of this learning process, and to better understand these acquisition and processing stages, the Gabbard case study was undertaken, which would focus less on the visualisation aspects. Gaining this knowledge contributes to the answering of research question zero as it reinforces the need for best practice throughout the entire process. This leads to visualisation outcomes potentially being clearer and completed quicker, due to encountering fewer problems which need to be resolved in the later stages of the process.

RQ1: How effective are current visualisation methods in communicating subsea survey data accurately and clearly?

The Gabbard case study does not attempt to review how effective current visualisation methods are against one another. It did, however, create opportunities to see which methods were being used in a live commercial project, and give a better understanding as to how the offshore energy industry operates in terms of using and reading visualisation outputs.

RQ2: What is the relationship between automation and 3D visualisation of subsea survey data?

There were opportunities during the author's placement as part of the Gabbard case study to automate data processing tasks which were being completed manually (discussed in more detail in section 8.5.2).

RQ3: What are the effects on the understanding of subsea survey data in the transitioning between digital and physical 3D representations?

During the Gabbard case study and commercial placement, there were no opportunities to involve physical representations of the datasets being gathered – mainly due to the tight deadlines for ADUS DeepOcean delivering this large-scale project. Fortunately, this project provided a large amount of high-quality subsea survey data which could later be used for experimental visualisation attempts (such as the 3D printed wind turbine shown earlier in Figure 4.13).

RQ4: What is the measurable value of innovation in 3D visualisation to the subsea surveying industry?

On its own, the Gabbard case study does not answer this question directly. However, it helps build a clearer picture of where the industry currently sits in terms of using and understanding visualisation methods (as mentioned in reference to RQ1 above). In this case study, the industry client was requesting deliverables in the form of 2D 'top-down' charts which used the more traditional rainbow ramp colours to define depth (an extract from a completed Gabbard deliverable is shown in Figure 4.11). In combination with the work undertaken throughout the Troll case study (chapter 7), the application of more developed visualisation techniques can be used to improve clarity and understanding of data over the methods currently being used.

8.3 Research themes

One of the key themes of the Troll case study was the automation of data tasks when compared to completing these manually. During the Troll practice, most visualisation tasks were completed manually, relying on expert tacit knowledge to produce the best results. This same approach was applied to the Gabbard data processing, though automation opportunities were identified for some of the more repetitive processing tasks such as removing 'zero points' (those at a vertical depth of zero, essentially tracking the path of the multi-beam sonar device) or outliers in the point cloud data which were not accurate because they were situated far below the seabed. Both of these issues could have been resolved by creating a relatively simple script which would remove data outside of the expected depth range; proving immensely useful when processing 1,258 data files.

However, in this project the senior data processor made the decision not to allocate time to creating automated solutions for these tasks, and so these were undertaken manually. This was due to the senior data processor believing that the additional development time would outweigh the time-saving that could be achieved. This approach is generally indicative of the subsea surveying industry as experienced by the author throughout each case study, where there is often a reluctance to stray from tried and tested working processes.

In addition to questioning the use of **automation**, the Gabbard case study addresses all of the identified research themes (chapter 3) to some extent, though is primarily centred on two themes - **pipeline** and **digital versus physical**.

Pipeline is particularly relevant as one of the key goals of this case study is to revisit earlier stages of the working processes – acquisition and processing – to provide a clearer understanding of how these might affect the final visualisation outcomes.

The Gabbard project also provided an extensive library of high resolution subsea survey data, and this was later used to create and print three-dimensional physical scale models – allowing for a *digital versus physical* comparison of different visualisations of point cloud data, and enabling a better understanding of the labour required in 3D printing subsea data.

8.4 Methodology

Throughout the Gullfaks case study, the **Explore Review Create** methodology (as introduced in chapter 6) was used. This included a particular focus on the author's reflection on practice as research.

The *explore* phase was the largest and most important during this case study – a commercial placement provided a unique opportunity to observe and participate in the acquisition and processing of data on a large-scale subsea survey project (section 8.5 discusses this in full).

Continually *reviewing* the work being undertaken helped understand the processes that ADUS DeepOcean have developed, such as how they continue to address the 74 factors which they believe impact the quality of data acquisition (ADUS DeepOcean, 2016). As with the contextual review, this also highlighted the lack of a similar system which could be used to grade data for visualisation and improve consistency in achieving strong results.

Finally, the majority of practical work was as a commercial data processor – preparing survey data for visualisation which could be provided as client deliverables – and so the primary task was in *creating* clean, organised and usable high-quality datasets from the raw sonar source data.

As the commercial project was task-oriented and focussed on providing a series of deliverables on-time, there was much less need to undertake this work in a cyclic iterative manner where the process was being continually improved and developed. As a result, the application of action and design research had smaller parts to play in this case study as the author's role was to complete smaller, more repetitive tasks to gain insight into the working processes, and observe the project as a whole.

8.5 Practice

The author's role in the Gabbard case study was comprised of two main stages. The first of these included observing the mobilisation of the subsea survey equipment by ADUS DeepOcean, and better understanding the acquisition of multibeam sonar data. The second, and larger of these two stages, was as part of the on-shore data processing team throughout the commercial project.

Building on the knowledge gained during the Troll case study on using different visualisation techniques, the author recognised that while previous focus had solely been on the visualisation part of the process, significant advances could be gained by better understanding the earlier stages that lead to visualisation - for example, where the data comes from, and the amount and type of work required to prepare it for visualisation. This placement with the ADUS DeepOcean team supports the author's understanding of data acquisition and processing, leading to the creation of more effective visualisations of subsea survey data when combined with the knowledge gained during the other case studies.

8.5.1 Acquisition, processing, and visualisation

As part of the ongoing research process, the author had earlier established a basic model for working with data, with three distinct stages – acquisition, processing and visualisation (originally introduced in section 4.5 and shown in Figure 4.5). Although initially presented as a complete model at the start of this research, it had been created and improved throughout each of the case studies, and this model was further developed as a result of the Gabbard case study which played the biggest role in understanding two of the three key stages.

Figure 8.6: Author's role in the Gabbard project

The Gabbard case study itself falls primarily into the 'acquisition' and 'processing' stages of the model (shown in Figure 8.6), although some experimental visualisation was later undertaken beyond the scope of the original case study.

The acquisition of multibeam sonar was introduced briefly in section 4.4 – using the ISHAPS (or Independent Sonar Head Attitude and Positioning System) process developed by ADUS DeepOcean. Figure 8.7 shows this system being deployed after it has been '*mobilised*' (constructed and tested, ready for surveying to begin). The author's initial involvement in this commercial placement was after the tendering process had been completed and the project aims were fully developed, and so started with mobilising the ISHAPS and preparing to acquire subsea survey data.

Figure 8.7: Photograph showing the ISHAPS being deployed as part of the Gabbard project

The mobilisation process lasted for two full days, and involved labour from up to nine workers at any given time (Figure 8.8). Ensuring that all of the equipment had been setup correctly is critical during this stage, as this affects the quality of the data being gathered afterwards. It is important that mobilisation is conducted with an awareness of addressing the factors previously identified by ADUS DeepOcean which contribute to good quality, high resolution surveying.

Figure 8.8: Photograph taken during the Gabbard mobilisation process

During the mobilisation process, the author had the opportunity to become part of the cyclic feedback loop referred to in both design and action research (in sections 6.1.4 and 6.1.5). Previous work undertaken by ADUS DeepOcean identified over 50 factors which can affect the quality of their multibeam surveying results (Dean et al., 2010), and this was developed further to include up-to 74 factors (ADUS DeepOcean, 2016). With ADUS DeepOcean continually working to improve their own surveying practice, this increase in knowledge helps avoid encountering the same issues during the next iteration of their workflow. It proved invaluable to see this structured approach in practice, as it would help inform the author's approach to visualisation, and raised the question of why there is currently no standardised, unified way of addressing data quality factors or creating data requirements beyond data acquisition. A set of guidelines which governed this would contribute significantly to generating consistency in gathering and working with high quality subsea survey data, whilst still creating the best results achievable – exploring this topic further could form the basis of future research, and a first proposal for addressing this is detailed in chapter 10.

It also became clear that mistakes or problems encountered during the data acquisition of the process would lead to bigger issues in processing or visualising the data later (or in extreme circumstances, lead to the inability to capture usable data at all). For example, during mobilisation, care was taken to ensure that the GPS data being recorded was as accurate as possible (down to centimetric accuracy on a moving boat). This would prove critical when trying to accurately overlap multiple segments of data, gathered during separate sailing passes. This is also something which will be further discussed as part of the Gullfaks case study (in chapter 9) where accompanying positioning data was not provided,[60] making the processing and visualisation of the data extremely problematic.

During the acquisition of the Gabbard data, it was realised that using a multibeam sonar device only facing directly downwards (as is generally the case) would not capture the best range of data possible. Although a downwards-facing sonar head would be useful in capturing the seabed surrounding the base of each wind turbine (Figure 8.9, left), it would not be suitable for surveying the turbine body as a ship could not be sailed close enough[61] to 'see' all of the structure.

[60] Positioning data wasn't provided as part of the Gullfaks data as it was not recorded during data acquisition and therefore does not exist.

[61] There were strict safely regulations (from both SSE and ADUS DeepOcean) in place throughout this project that included maintaining a safe distance from each turbine.

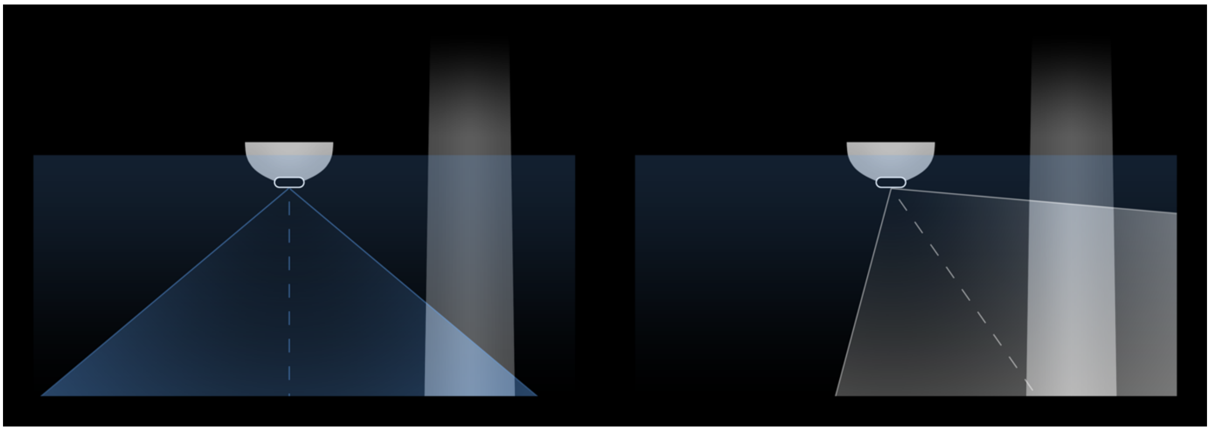

Figure 8.9: Diagram showing the difference in scan coverage between a downward-facing (left) or angled (right) multibeam sonar device

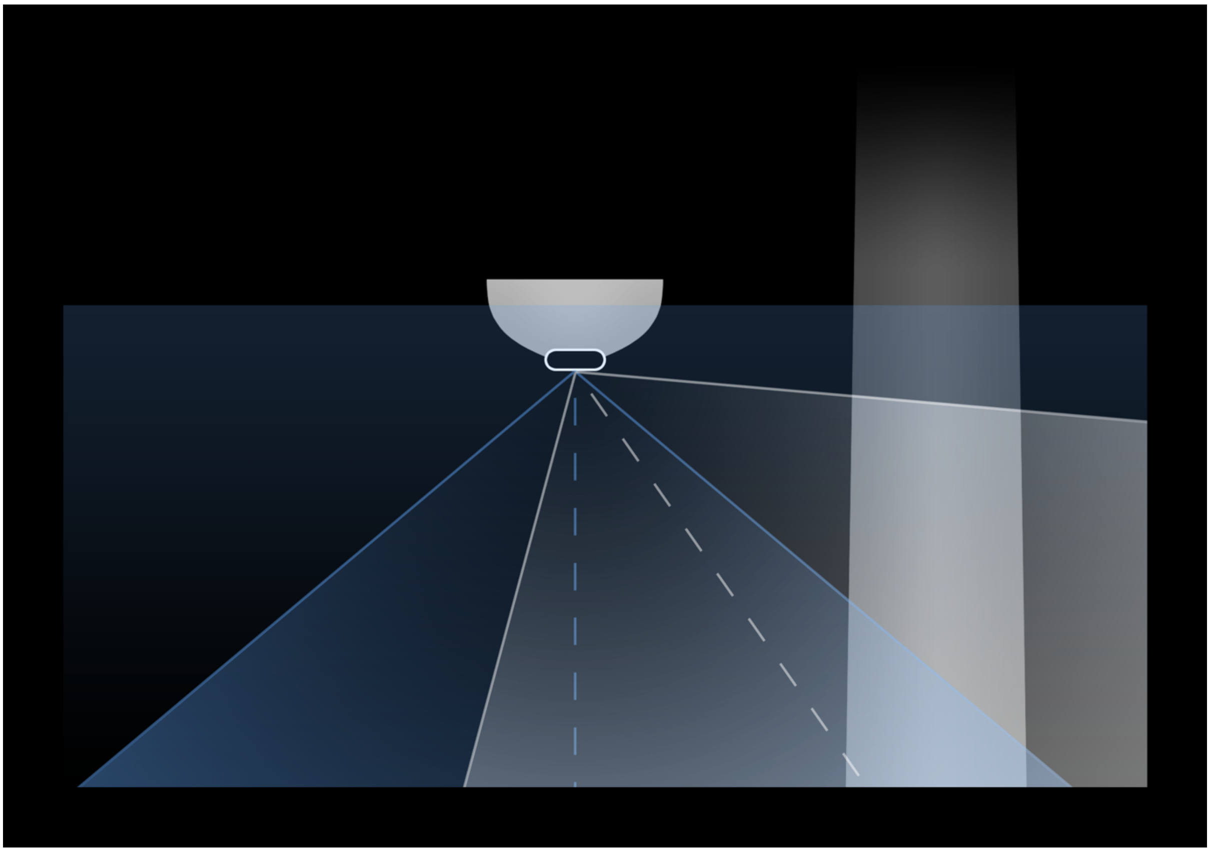

Figure 8.10: Diagram showing combined scan coverage of an offshore wind turbine when using both downward-facing and angled multibeam sonar devices

As a result, ADUS DeepOcean also surveyed each turbine with a multibeam sonar device angled slightly upwards, giving an improved range of visibility and coverage in doing so (an example of this is shown in Figure 8.9, right). Combining both types of survey pass would offer the best results in eliminating blind spots from the resulting datasets, and Figure 8.10 shows the improved overall scan coverage that can be achieved when using these together.

Throughout the Troll case study (chapter 7), the author's focus and development had been primarily on the visualisation stage of the pipeline. In an effort to improve the overall process of visualising subsea survey data, working with ADUS DeepOcean to acquire data proved an invaluable activity. It gave first-hand experience of setting up survey equipment, an understanding of what factors could influence the quality of the data being gathered, and the opportunity to see all of this in a real-world setting and application where the results were commercially critical and time-sensitive.

Beyond assisting during mobilisation and observing the acquisition of data, the author's primary role in the placement with ADUS DeepOcean was in processing the acquired data that was now ready for delivering visualisation outputs to the client – either in GIS format by the hydrographic surveyors or in a 3D (and potentially interactive) format by the 3DVisLab.

8.5.2 Processing data effectively

Processing the survey data for all 140 wind turbines and linking cable corridors proved to be an extremely time-consuming process, as it was entirely manual – relying on the expertise of those familiar with subsea survey data. Initial estimates from ADUS DeepOcean suggested that data processing would take approximately 15 days, though upon completion, it had lasted for 40 days in total – sometimes with two workers processing data during this time.

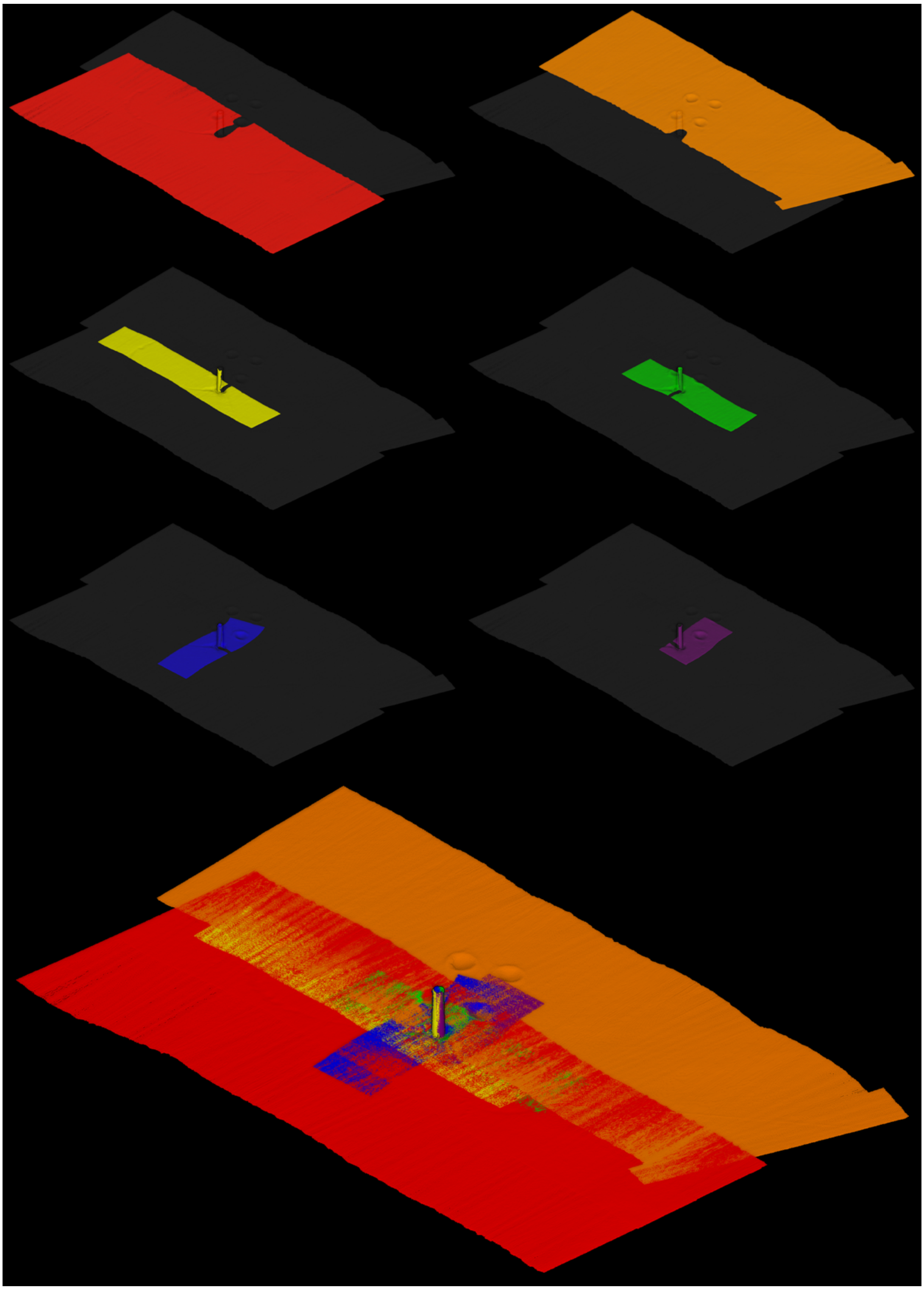

Figure 8.11: Image showing six different passes as part of a single Gabbard turbine dataset (coloured for clarity), the lower half shows the combined set of passes

Data processing started whilst it was still being acquired, and all of the processing was completed using QPS Fledermaus – software designed for geospatial processing and analysis, and part of a range of compatible software packages which can be used to create a pipeline for acquiring and processing multibeam sonar data effectively. This also allowed for all of the individual sailing passes (or lines) over an asset to be maintained as separate data files within one larger project dataset. Figure 8.11 shows a complete set of passes for a single subsea asset, and their contribution to a complete dataset. In addition to viewing the diagram, the three-dimensional point cloud data shown is available in the data repository (Data 8.1), without colours added.

Data 8.1: Data repository > CS2 Gabbard (Data) > GAA01 [FULL] > GAA01_Lines.BIN

This approach would allow only the best passes to be selected, creating a 'final' version of each subsea asset where any problem passes could be easily removed or fixed. Although this would add to the overall processing time per turbine or cable corridor, it would build-in greater flexibility which could be required later, where deleted passes cannot be re-added if they were previously removed.

The first stage of processing involved removing all of the 'bad' or unwanted data points – such as 'zero depth points' captured along the route of the multibeam sonar device (as there cannot be other objects there), or points which sat significantly below the seabed (due to the occasional error in how sonar data is captured).

Despite the acquired survey data being three-dimensional, this part of the processing and data cleaning was much simpler in a two-dimensional 'side-on' view – where the profile of the seabed and turbine could be clearly seen. As shown in Figure 8.12 and Figure 8.13, it is easy to see which points can be removed quickly and with little deliberation as to what they might represent. The points for removal were easily selected using a box selection method – just as you would with a group of files and folders on any home computer – and then deleted. Extra care was taken – typically by zooming in closer – with any points immediately below the seabed or close to the top of the turbine, so that detail was not removed unnecessarily.

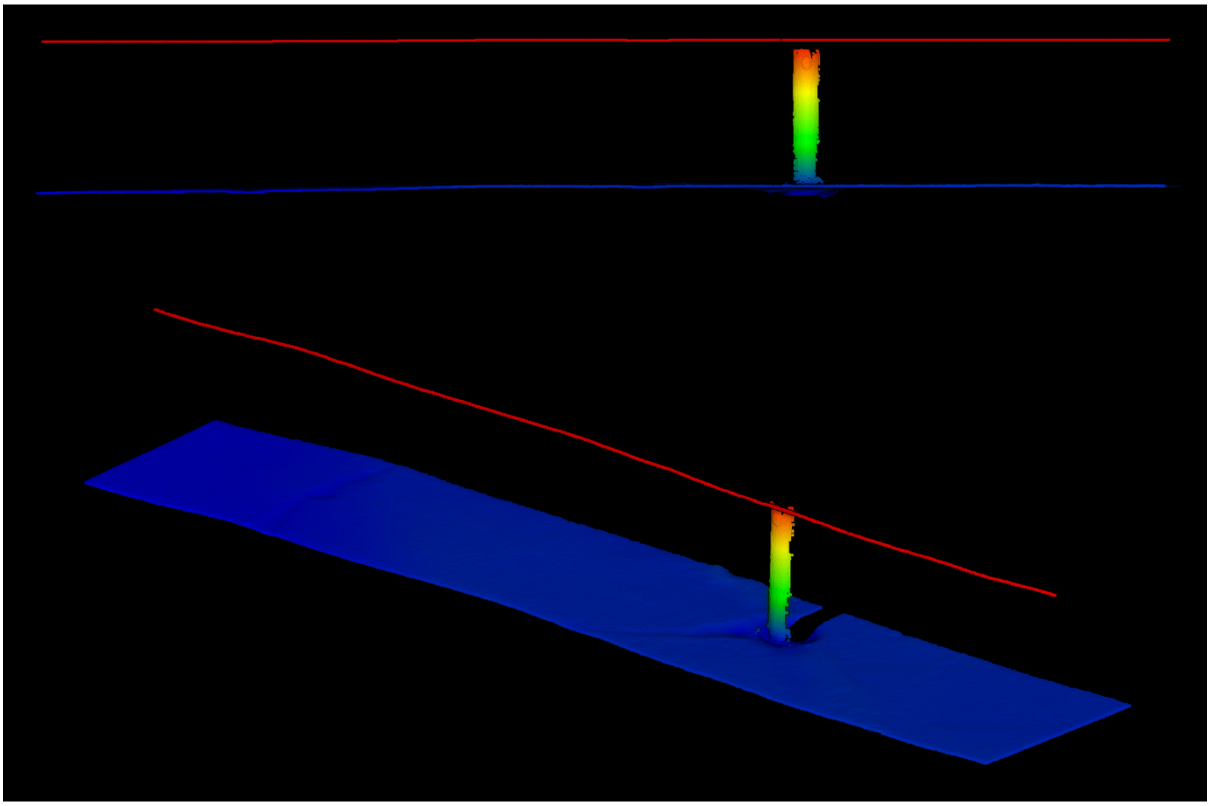

Figure 8.12: Example of 'zero depth points', represented by the red line above the cylindrical wind turbine base

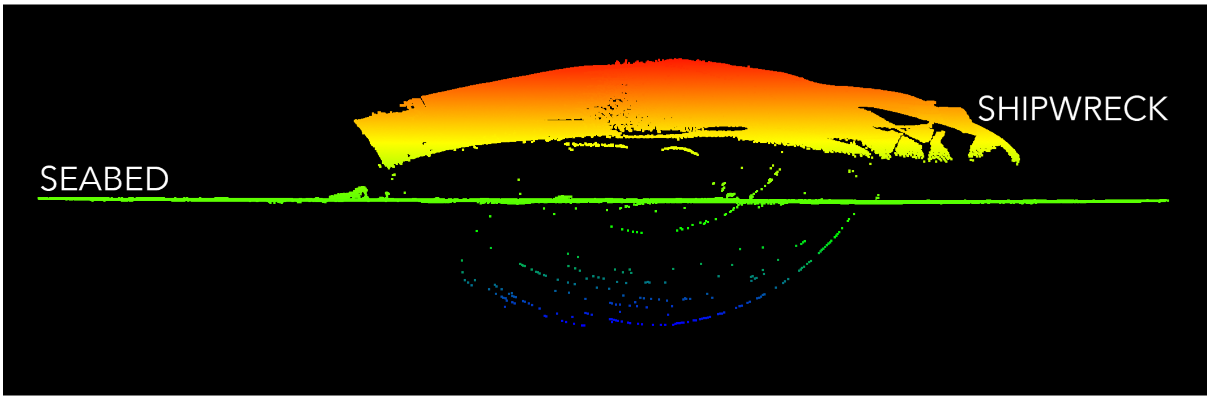

Figure 8.13: Point cloud data showing data incorrectly (and impossibly) captured below the seabed

There was also some manual clean-up involved in tidying the cylindrical shape of the wind turbines, as these were often ‘fluffy’ and poorly defined due to multiple sailing angles and passes being required to capture them fully. Figure 8.14 shows three views of a single pass alongside one turbine, where the edges of the data are not as dense or clearly defined as the central part that was facing directly towards the multibeam sonar device.

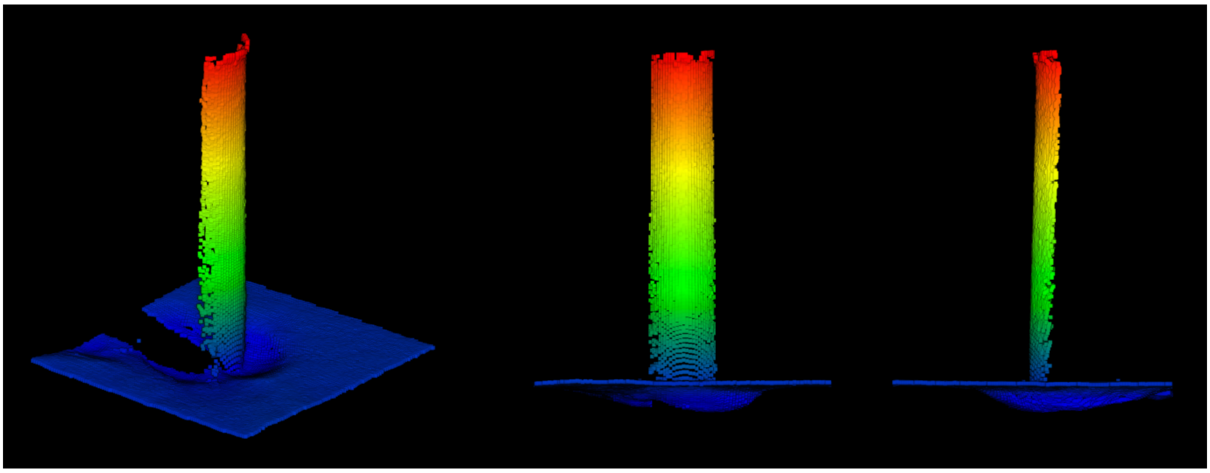

Figure 8.14: Three views of the same post-processed sonar dataset, a Gabbard turbine, which show the lack of definition and point density towards the edge of the cylindrical body

This second stage of cleaning and preparation was much more time consuming and was approached on a more bespoke basis than the initial steps undertaken. First, the overlap between passes was removed using the same box selection technique used already – though requiring good control of the three-dimensional viewing format of the data to ‘see’ the turbine clearly in the point cloud data, and to ensure that only the noisy edges were being selected for removal (Figure 8.15). Once these edges had been removed from each of the passes containing the turbine, they were combined once more and then a finer level of point removal would be undertaken again using the same select and delete approach, though paying more attention to maintaining the shape of the turbine and not creating any gaps in the data by removing too many points.

Finally, once the post-acquisition processing (such as applying GPS corrections) and cleaning had taken place, the data was exported out of the proprietary QPD file format to a more generic XYZ format (where it was stored in CloudCompare BIN files so that individual sections could not be lost or confused with other assets). Migrating to this format ensured that anyone could easily open and view the completed data files, which would now be ready for visualisation as final deliverables (Data 8.2).

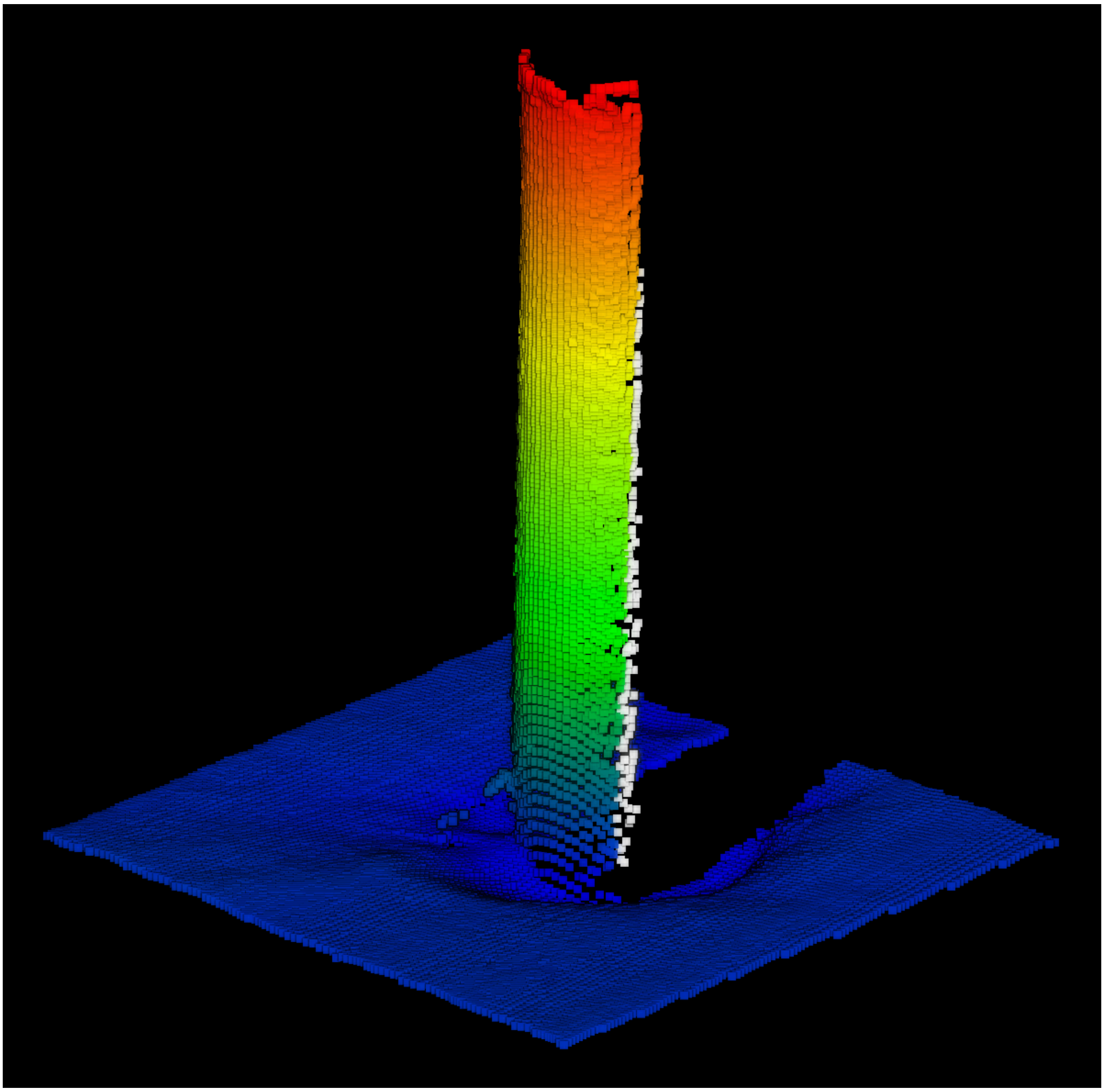

Figure 8.15: Gabbard dataset showing a selection (in white) of points which could be removed, provided another pass offered better quality data points in their place, resulting in an improved quality of completed dataset

Data 8.2: Data repository > CS2 Gabbard (Data)

Throughout the processing stage, there were no delays in receiving data to work with; as processing took significantly longer than anticipated, the acquisition team were capturing data quicker than it could be cleaned and returned. Having undertaken a significant amount of research and development into their acquisition process and methodology, it was clear that ADUS DeepOcean's awareness of these elements contributed to their ongoing success in acquiring high quality data.

During the first stage of processing, which involved removing the 'zero' points along the path of the multibeam sonar device, the author realised there was an opportunity for innovation and improvement. These points effectively had a depth value of zero, and could be removed automatically, removing the intensive stage of manually checking and removing these across 1,258 individual data files (whilst also avoiding the loading times of so many files associated with this step). This improved approach was suggested to the senior surveyor who was managing the data processing, however the resulting decision was not to spend time on development and instead to focus on completing files as originally planned. Although the author was confident that the development time required to automate such a process would be quicker than undertaking it manually, the senior surveyor believed this to be unpredictable and made a decision based on their own experience, choosing to use the 'tried and tested' approach with which they were familiar.

Processing data files individually (with perhaps eight or ten individual files each) led to a huge increase in asset completion time due to the frequent duplication of actions.

This led the author to identify an opportunity for improvement: combining and cleaning multiple passes as a single point cloud. This new approach of working with a single data file per asset was suggested to the senior surveyor who was responsible for all data processing as part of this commercial project, and the decision was made to maintain separate files. Although unclear as to the rationale for this decision at the time, on reflection this turned out to be the correct decision as performing the fine-detail cleaning during the last stages was much simpler when there was a smaller area to focus on and each section could be isolated. This had been a decision made intuitively by the senior surveyor at the time, but reflected the industry expertise in approaching these types of tasks.

Despite the volume of the data being generated and requiring manual processing, all of the 1,258 data files were eventually cleaned, and the results were a series of high resolution datasets which could be used to generate the client deliverables. These are available for viewing in the accompanying data repository, organised into a series of individually named folders per site asset (Data 8.2).

At this point, the author's role in the project was finished, and work undertaken by the other team members would continue into the final stages. The opportunity to gain first-hand experience of both the acquisition and processing of subsea survey data would fill significant knowledge gaps in working with this type of data, and help inform the author's evolving approach to visualisation. In addition, the chance to undertake this work in a real-world commercial setting was invaluable as it provided the most authentic experience to learn from.

8.5.3 Working as part of a large-scale commercial project

As part of the ADUS DeepOcean project team responsible for surveying all 140 wind-turbines and 152 inter-array cables (ranging from 800m to 5200m each), this case study was an opportunity to work with industry experts in the field on one of the largest projects they had previously undertaken. It was a learning experience for all involved and took considerably longer than expected. Initial estimates suggested a survey duration of 10 days on a 24-hour operational basis, where the survey took a total of 39 days, and was largely affected by three main issues: unpredictable weather conditions, delayed arrival of equipment rentals, and adding additional survey days to ensure the site coverage requested by the client was achieved. High-resolution subsea surveying is influenced by a significant number of factors (ADUS DeepOcean, 2016) and sudden changes in weather conditions can result in data becoming unusable. This is often due to precise control of the survey vessel becoming difficult, resulting in planned sailing lines not being followed closely enough, or the spread of sonar pulses becoming sparse or uneven, requiring additional post-survey correction (which is not always possible if the appropriate supporting equipment is not used). With careful planning and an experienced crew, most of these issues can be resolved, though unsuitable weather remains a constant and uncontrollable challenge with surveying often becoming a waiting game.

Communication between team members was critical, and all were in attendance at the start of the project to organise and plan the best ways of working as a team. Beyond the initial face-to-face planning meetings, email was used for almost all communication (with team members located across Scotland, England, and the Netherlands), and data files were shared internationally using sturdy, weatherproof USB drives sent via tracked courier services. Though the author believed this to be a strange solution at the start of the project, it was later shown to be faster than cloud-based file transfers due to the significant size and volume of data files being gathered and shared for processing. However, this was a far more expensive solution due to the added cost of international priority shipping, though ADUS DeepOcean found the importance of speed to far outweigh the extra costs on such a project. This decision was significant in reducing any bottlenecks in data processing caused by data sharing being delayed. It is important to note that during the later stages of the Gabbard data acquisition some files were transferred using online services, though these were typically a smaller number of files used to 'patch' any coverage or quality issues which had been found in processed datasets.

Throughout the surveying process, an on-shore team (including the author) continued to process data daily. Typically, each wind turbine consisted of 6 passes (an example can be found in Data 8.1), and inter-array cable lengths contained 1-2 passes (an example can be found in Data 8.3). Some assets required multiple passes to ensure there were no blind spots in the data, or to correct inaccurate sailing lines. All of these passes had to be processed individually, combined and returned to the senior data processor for inspection. Completing data processing efficiently was essential because if there were any problems with the data, the mobilised acquisition team could re-survey an area if required to do so. This would have proved significantly more challenging – and expensive – to resolve if all of the processing took place afterwards, when the acquisition team was no longer on-site and able to correct any problems.

Data 8.3: Data repository > CS2 Gabbard (Data) > GAB019 > GAB019_Lines.BIN

In addition to providing first-hand experience of preparing for and acquiring subsea survey data, the Gabbard case study was an opportunity to better understand the earlier stages of the data lifecycle – something which had not been experienced by the author as part of the Troll case study which focused on creating different types of visualisation. An improved understanding of both acquisition and processing has enabled the author to approach the entire process, including visualisation, with a stronger awareness of each of the interlinking core elements. Though understanding individual stages is essential, it is important to also consider the data lifecycle as a whole because each stage is dependent on the others and should not be considered as an individual component with no connections. For example, surveyors should be aware of how tasks they undertake can influence the visualisation work later undertaken (such as making decisions about whether to include positioning information alongside survey data).

In a broader sense, visualisation practice suggests that some form of best practice should be applied, leading to consistently generating the best quality data which can be used to create visualisations which are clear and do not mislead or misrepresent. The contextual review and practical experiences of the author found no evidence of this type of guidance being applied across the offshore industry, particularly to the subsea visualisation process.

Armed with a strong understanding of the visualisation stages, and knowing the best condition for data reaching this stage in good condition, the author has been able to offer internal feedback to colleagues undertaking the earlier acquisition and processing stages. Just as ADUS DeepOcean identified factors which influence the quality of acquisition, it is appropriate that both the author and the 3DVisLab contribute their knowledge of visualisation requirements to help shape the way in which data is gathered and prepared – ideally working as part of a multi-disciplinary team where knowledge is shared and each member can help one another.

8.5.4 Providing a library of data

This case study also allowed access to a huge collection of high-resolution survey data – allowing for further research and development beyond the limited scope of visualisation that the projects client required, such as experimenting with creating surface models for 3D printing.

The advantage of using the Gabbard data is the added confidence in knowing that the acquisition and processing were carried out to a high standard, rather than continuing to work with data which may have an unknown or uncontrolled origin. The Gabbard data would also be much simpler to work with experimentally, as wind turbines are far less structurally complex than the previously attempted Troll E4E5 dataset.

Following on from the experimental stereoscopy work completed as part of the Troll case study (sections 7.5.3 and 7.5.4), the Gabbard data was used by the author after the commercial project had finished – Figure 8.16 shows an example of this, as a photograph of a 3D printed plastic model. In this image, the base panel represents a scaled area of seabed, originally 100x100m, and the central column shows the base of a wind turbine. In contrast to its counterpart (Figure 4.13), this printed model shows a wind turbine which does not have a scour problem around its base.

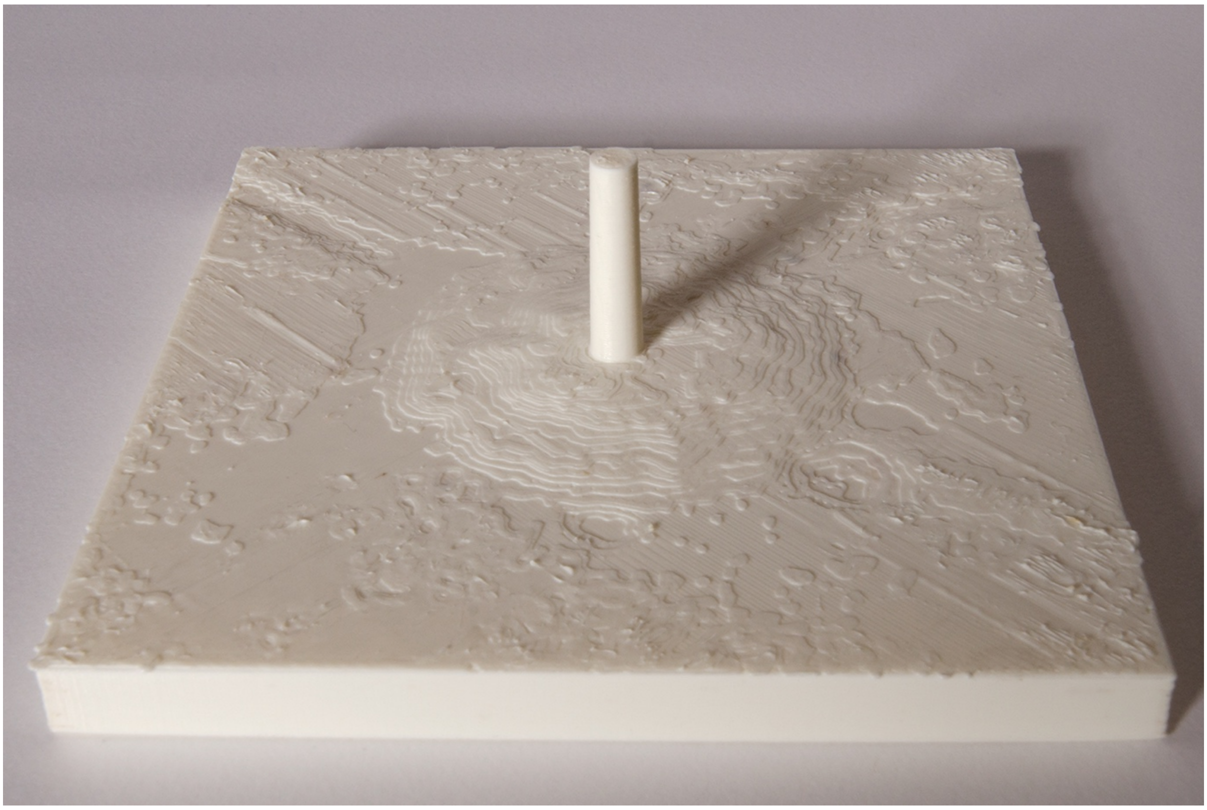

Figure 8.16: Example of a 3D print, created by the author using data gathered during a subsea survey (showing a wind turbine monopile unaffected by scour)

Creating two scale models (the first originally shown in Figure 4.13) was only possible with access to quality data, and with the practical knowledge gained during both the Troll and Gullfaks case studies. In addition, due to the relatively simple and flat nature of the seabed, automatic surfacing methods (using CloudCompare) provided a simple meshing solution, and the cylindrical wind-turbine was manually added.

8.5.5 Data grading?

As part of the Gabbard placement, the author was able to compare each of the key stages of the visualisation pipeline – how ADUS DeepOcean approached data acquisition and data processing, and how the 3DVisLab undertook data processing and data visualisation. As was to be expected, each of these steps were approached differently, using the expertise and knowledge of specialists involved at each stage. It is important to note that throughout the Gabbard project, there was typically a chain of specialists each undertaking their own defined role, one after another, rather than a team of generalists working on completing a series of tasks together.

Employing specialists was important in completing each component to a high standard, but may have been limiting to any subsequent stages of the pipeline, as each specialist may not have had an understanding of the next stage in the process and any work that they could undertake to improve the data handover. For example, when combining multiple survey passes, having accurate positioning data significantly reduces the time taken to complete this task. The 3DVisLab has often been given data without positioning information (an example of this forms the basis of the Gullfaks case study, in chapter 9), and so if the surveyors are aware that this is considered a data requirement for processing and visualisation, including this can help enable smoother data handovers, removing potential problems and reducing the amount of time needed to resolve any issues that may still arise.

However, it became apparent that while ADUS DeepOcean adhered to a series of identified and measurable factors in data acquisition always ensuring the highest quality, there was no similar structured approach to subsea survey data processing and visualisation which could be adopted. Having clear and defined expectations of the way in which data is acquired has enabled high-quality data to be consistently gathered. By adding requirements for processing and visualisation, this could be further expanded to improve the entire pipeline and therefore the final outcomes.

Grading data and having requirements beyond those of surveyors acquiring the data would also offer a clearer indication as to what could be achieved with a particular dataset, and how long it might typically take to produce the desired results. Just as ADUS DeepOcean has a preference towards experts undertaking specialist roles, creating a shared language and data grading system would not only allow this to continue, but in a way which is informed by all of the specialists at each of their respective stages – working together and sharing knowledge as part of a multi-disciplinary team with a single goal.

Expanding the understanding of factors which contribute to good subsea data processing and visualisation is a substantial task requiring input from a large number of experts throughout each of the stages. As part of this research, each of the three case studies have contributed to developing this understanding of *good data*, and identified ways in which grading data could prove beneficial. This includes the practical work being undertaken in a more efficient manner – encountering fewer problems, and achieving results in a shorter timescale – which would impact positively on the ongoing research into visualising subsea survey data.

However, the author has recognised that fully realising such a project is beyond the scope of this investigation, and as a result, a first attempt at starting this process is detailed in chapter 10. This chapter proposes a suitable data grading scale as a first step towards improving data capture and quality awareness when visualising subsea survey data. This is achieved by creating a system for evaluating acquired subsea survey data, and identifying the value and usefulness of each dataset before visualisation begins.

8.6 Findings and reflection

Although smaller in scale than the other two case studies, the work undertaken as part of the Gabbard project team offers a significant amount of insight into stages of the working pipeline which were previously unknown to the author. In addition to improving the author's knowledge and understanding of subsea survey data acquisition and processing in particular, it proved mutually beneficial to ADUS DeepOcean who gained an external observer able to offer new views on the work being completed.

One of the author's primary objectives as part of the Gabbard project team was to observe and better understand the acquisition and processing stages of the data lifecycle, which capture and prepare data for visualisation. The need to undertake this was a result of the work previously completed during the Troll case study. The additional knowledge gained observing the practical elements of the pipeline in a real-world setting contributed to the author's tacit knowledge and understanding in both working with the surveying team and later generating visualisations.

In addition to better understanding the overall pipeline, the project created an opportunity for an academic observer to provide direct feedback on the commercial processes of ADUS DeepOcean. It became clear that during the two main stages – mobilisation and data processing – there were both strengths and weaknesses. As discussed earlier, the project duration was noticeably longer than anticipated, and so acknowledging the strengths and addressing the weaknesses (through the author's role as reflective practitioner) would prove beneficial in improving and streamlining the next project of this size that would be undertaken by ADUS DeepOcean.

Due to the regularity of the mobilisation process as conducted by ADUS DeepOcean, the process as a whole was not only a requirement but a strength in itself. One of the key benefits of their established mobilisation process was the continued testing which was undertaken – ensuring that every piece of equipment worked correctly alongside all of the others, and minimising the potential for problems when surveying began. As a notable benefit to the author, it was an opportunity to work with experts and ask questions about the equipment and how things worked.

However, there were some observations made during mobilisation which would suggest one key improvement – the inclusion of a single and clear leader or project manager. Without this, there were often too many different views and decision-making became more challenging. Furthermore, the author found that without a single point of contact, it was difficult to get a clear indication of duties and responsibilities as part of the project, though this seemed to be less of an issue with the more experienced members of the team who were already aware of the tasks they needed to complete.

During the author's role as data processor, some of the weaknesses from mobilisation were seen here as well – in particular, lacking an understanding of duties at the start of the work being undertaken. In addition to this initial confusion of roles, due to the volume of files needing to be processed and the estimation of time to complete being so short, some of the data processing had become rushed – this resulted in a lack of proactive quality control, and some mistakes were made. For example, an error in height correction resulted in a depth misalignment in around 140 data files. Had this not been noticed, more than ten percent of the project data would have been vertically-positioned differently to the rest. As with any commercial project, maximising profit and efficiency are key, though it should not be at the expense of care and accuracy, as this ended up taking longer to resolve than it would have taken to double-check in the first instance.

On reflection, one significant change to the data processing stage the author would suggest is a clearer indication of overall processing completion or progress. This could take the form of a dashboard of some sort which would give a better approximation of when the processing might be finished, perhaps showing how many assets have been completed and how many have yet to be acquired, processed or visualised. Figure 8.17 shows an example of a fictional dashboard created by the author. Such a tool would assist in reporting, and also offer an insight into managing data processors as an assignable resource – for example, having too much data arriving and not enough people to process it creates a bottleneck affecting the tasks beyond data processing.

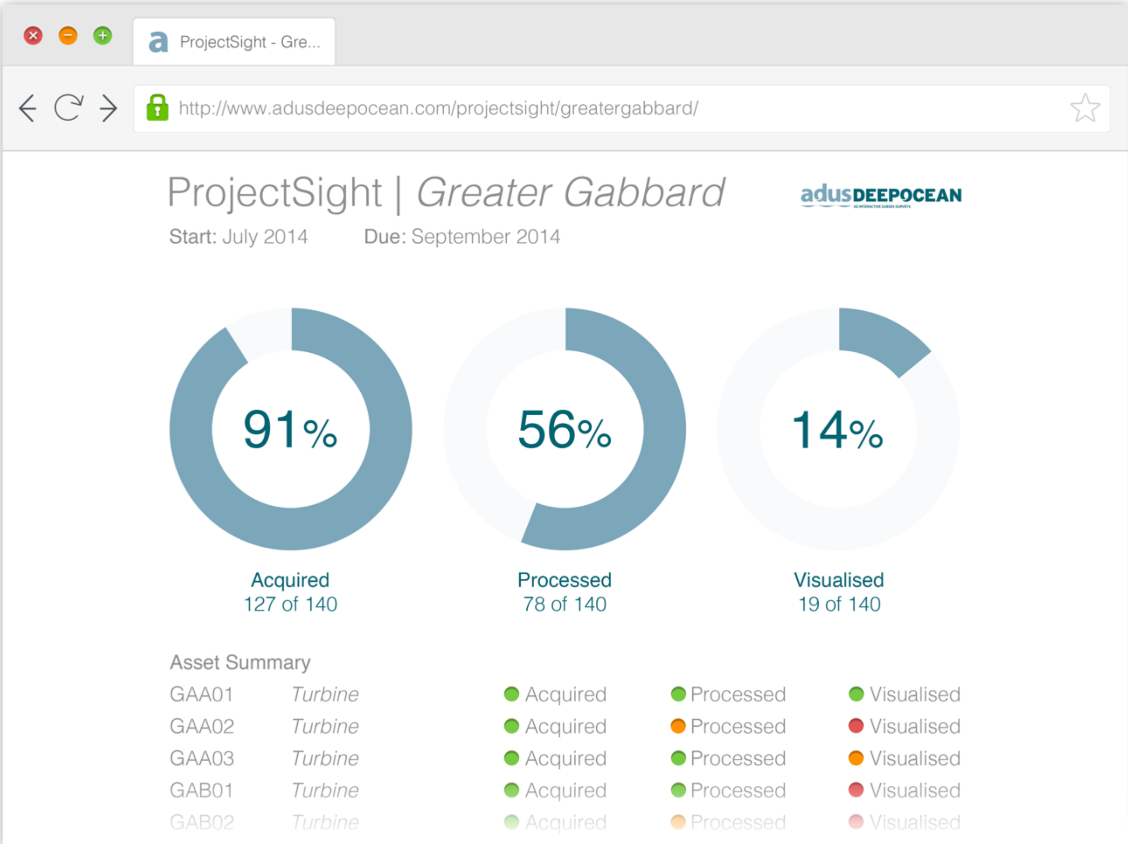

Figure 8.17: Example of a project dashboard, created by the author, which could be used to manage large-scale surveying projects

As discussed earlier in this case study, there were also opportunities to automate simple or repetitive tasks which were generally undertaken manually. Given the addition of a small amount of development time, these could assist in streamlining the data processing stages. On later reflection however, the author better understands the decision of the senior surveyor not to undertake this as part of a live project, where it was seen as an unpredictable task which may not yield immediate results and time was critical.

Finally, although there were several areas of improvement identified during the data processing stages, it was not without its strengths. Much like mobilisation, ADUS DeepOcean followed a tried and tested approach to data processing – one that could be relied on under pressure. This meant that there was less opportunity for development and experimentation, but similarly offered less opportunity for unknown problems to arise – an important factor in reliably processing data under the growing pressure of shortening deadlines. In addition, with the author taking on the role of data processor, it created a unique opportunity to work on a live commercial project with leading industry experts, and fully understand all of the work that goes into hand-processing data, which could later be used as a research resource. It also helped the author better understand all of the hardware and software which is typically used through acquisition and processing. The placement as part of this case study also offered insight into how ADUS DeepOcean undertakes projects with an awareness of the factors which can affect the quality of their data acquisition – something which led to the author considering the creation and application of data grading throughout the entire data lifecycle (introduced in section 8.5.5, and developed further in chapters 9 and 10).

Although the Gabbard case study offered little in the way of directly undertaking visualisation work and developing the ways in which data is presented, it built upon the first case study and helped inform the stages of the process which Troll did not explicitly address. The increased knowledge and understanding from each of these case studies would later be applied to a problematic dataset as part of the Gullfaks project.

8.7 Future work

Beyond the strengths and weaknesses of the practical work undertaken, the author realised a particular interest in the deliverables which the client had asked for – a series of top-down PDF charts, each showing an individual asset using the traditional method of contour mapping and 'rainbow ramps' (as shown originally in Figure 4.11).

As the primary focus was on completing the data processing as part of a commercial project, there was not enough of an opportunity to investigate these deliverables further and why they were requested specifically. It is the author's belief that better visualisation methods are both available and achievable as the acquired data was three-dimensional and of a high quality.

Investigating this topic in more detail could form the basis of future work, with the goal of better understanding the client's choice of deliverables and why they felt these were most appropriate or useful. It would also be relevant to explore how typical this approach is in the broader subsea surveying industry, and whether they were aware of any different visualisation options which could have been made available to them.

9 Case Study 3 – Gullfaks

As the third case study presented as part of this investigation of subsea survey data, Gullfaks was an opportunity for the author (in collaboration with the 3DVisLab) to undertake specialist processing and visualisation techniques in an attempt to recover data containing extensive errors and noise. This data had previously been worked on by more than one other company, and they had been unable to visualise this in an effective way, so the data had previously been labelled as being of no use or value.

The practical work undertaken as part of this project was initially completed during a three-month window, starting in December 2014 and finishing in February 2015 with a client visit to present the results in Stavanger, Norway.

In the following sections, background information on the Gullfaks project will be provided including site details, reasons for surveying, and details on the collaborative elements required in undertaking this work. This is followed by an investigation of the practical work undertaken and the findings and reflection generated throughout.

9.1 Gullfaks C4

Gullfaks is an oil and gas field located in a region of the North Sea near Norway (Figure 9.1). Prior to the area's ownership being allocated, it was referred to as 'Gullblokken', or 'The Golden Block' (StatOil, 2016). After the area was discovered in 1978, production started in 1986 and it now consists of three production platforms – Gullfaks A, B and C – across a site depth of 130-220 metres.

Production peaked in 1994 when the Gullfaks field set a production record of 605,965 barrels for a single day (StatOil, no date). Although considerably lower now, production is still underway more than 30 years later, and ongoing technological development continues to aid production.

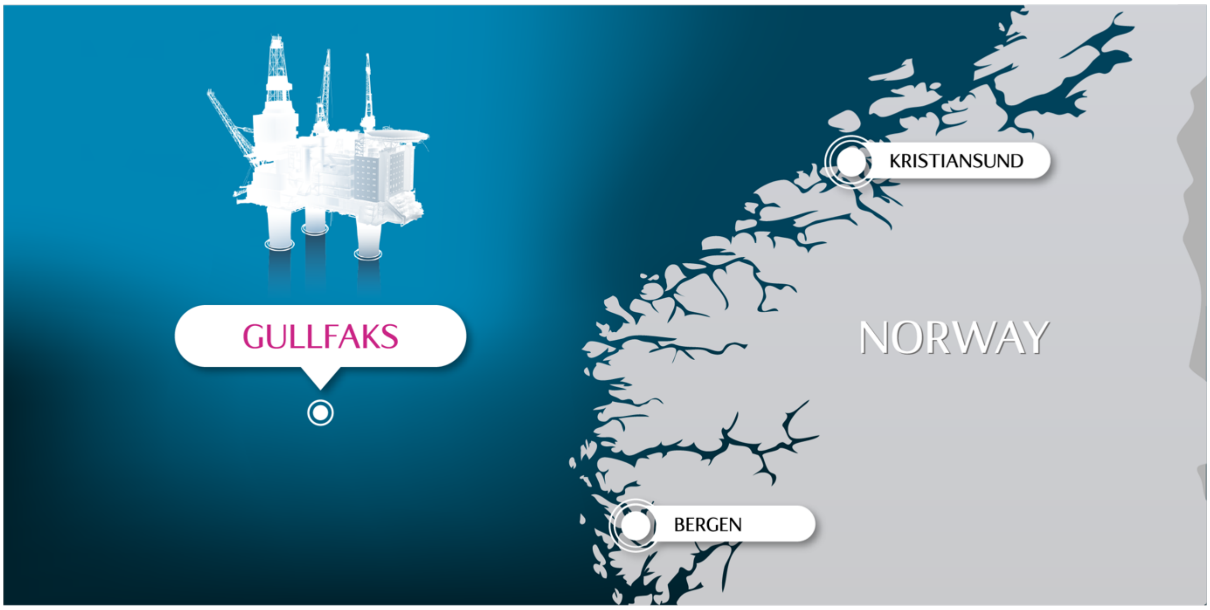

Figure 9.1: Location of the Gullfaks oil and gas field (StatOil, no date)

The dataset that ADUS DeepOcean received forms part of Gullfaks C, which began production in 1989, and sits 217 metres below sea-level. This is exceptionally deep and therefore problematic for gathering accurate data – TDI Advanced Trimix Divers are considered "some of the most elite divers" and will reach a maximum depth limit of 100 metres (TDI SDI, no date). As a result, inspection and maintenance of these assets proves to be difficult, and so the use of sonar technology becomes extremely relevant.

In late 2014, ADUS DeepOcean were approached by the client regarding visualisation of two datasets, each containing a different version of the Gullfaks C4 towhead. Referred to as 'hot' and 'cold' states, each of these represented the towhead during operation and after shutdown, respectively. The high pressures and high temperatures of the gas flowing in the pipelines causes expansion and movement between operational and non-operational states, and the client was interested in examining the difference between each of these (Figure 9.2).

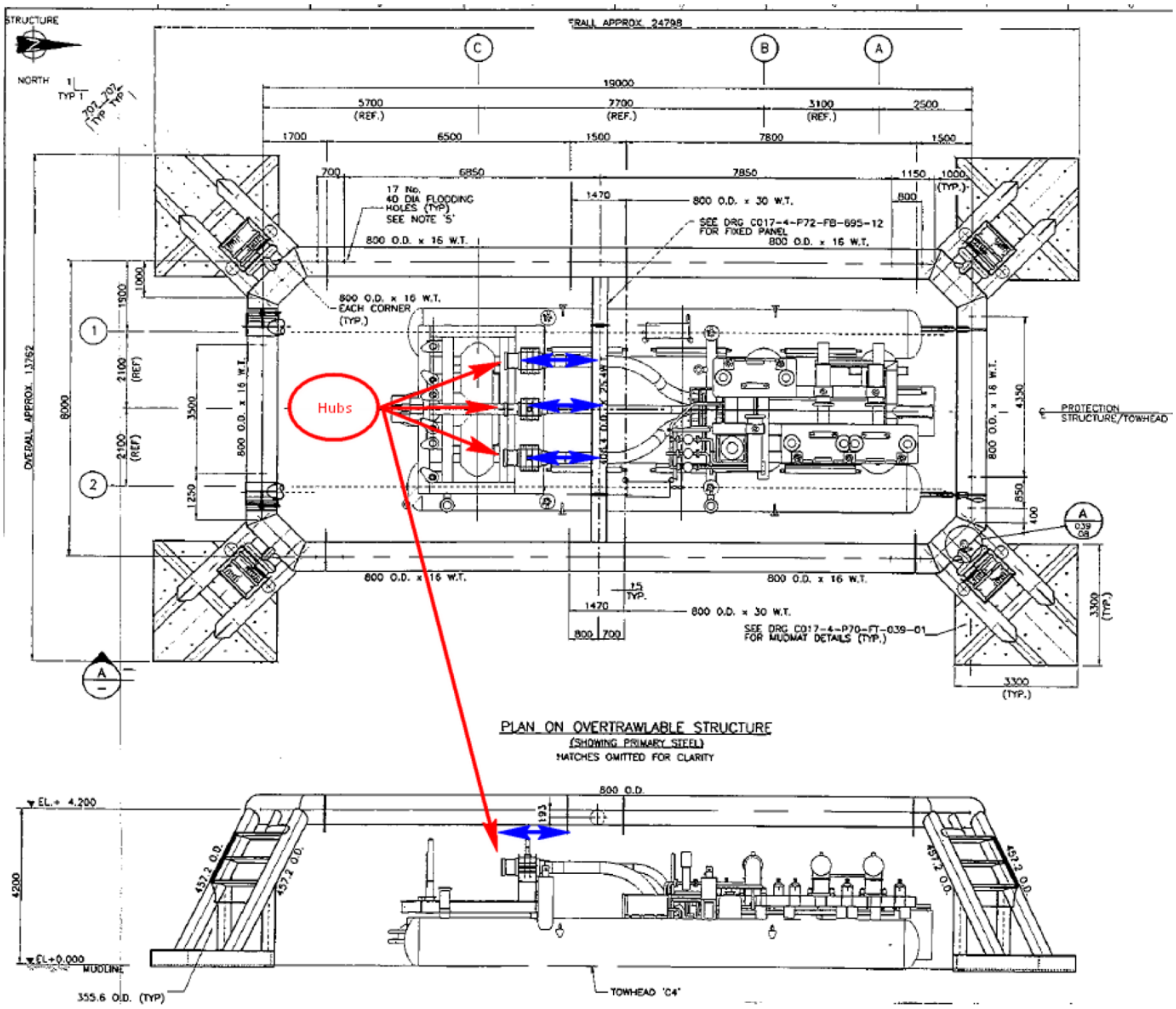

Figure 9.2: Technical diagram showing the Gullfaks C4 structure - the client was interested in measuring the movement, if any, of the labelled hubs (image provided by ADUS DeepOcean)[62]

[62] Figure 9.2 and Figure 9.3 are the best-quality versions of images made available by the client. This proved to be problematic in trying to understand some of the finer details or determine the written measurements, and as a result were primarily used to identify the approximate shape and dimensions in reconstructing the subsea structure.

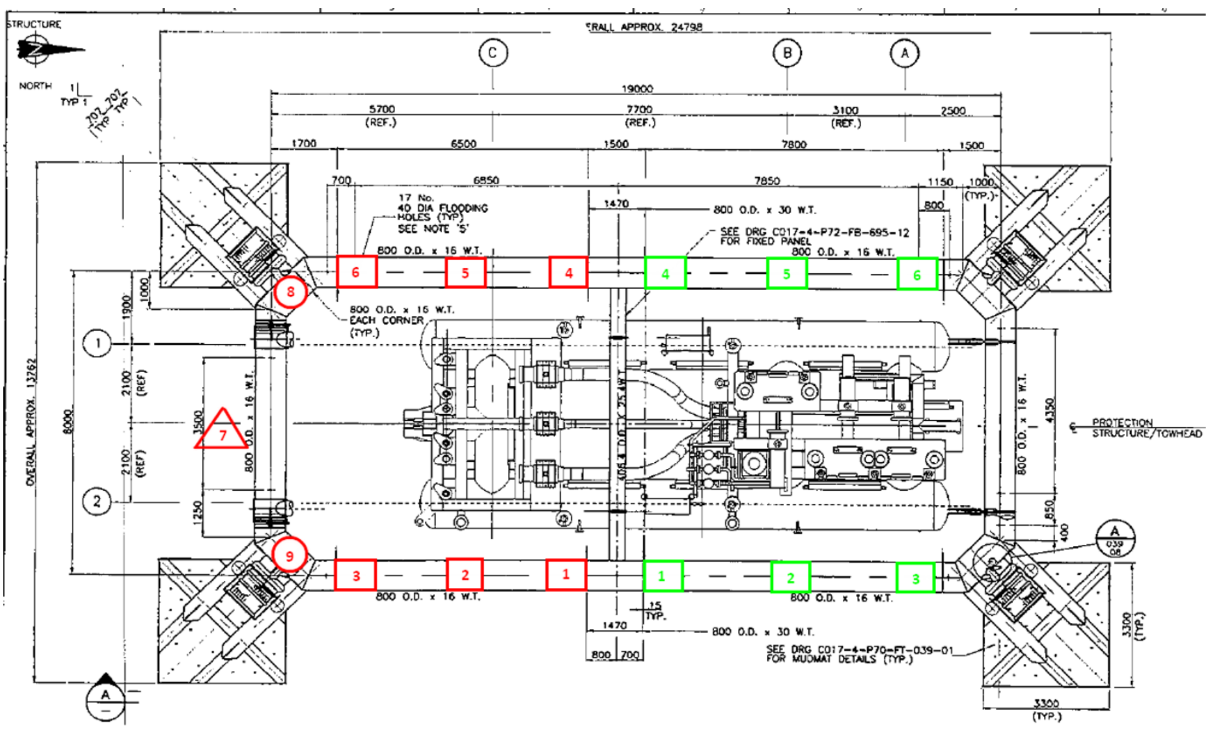

Figure 9.3: Technical diagram showing the Gullfaks C4 structure and the numbered scanning locations used during data acquisition (image provided by ADUS DeepOcean)

Originally, the client had proposed the use of Long Baseline acoustic metrology[63] to measure key points on the structure, but this was not possible during the project's short duration. Instead, the original contractors undertook a series of high-resolution sonar scans of the towhead protection structure (the scanning locations are shown in Figure 9.3), using a Teledyne BlueView sonar system magnetically clamped to the structure (Figure 9.4 shows a computer-generated example of this). This approach resulted in a series of individual scans which could then be co-located (or registered) during processing, giving a complete scan of the towhead – this would not be georeferenced using real-world coordinates but would create a relative dataset of each state, allowing the hot and cold variants to be compared using known fixed structural points.

[63] A technique using multiple subsea transponders to triangulate position with a high level of accuracy.

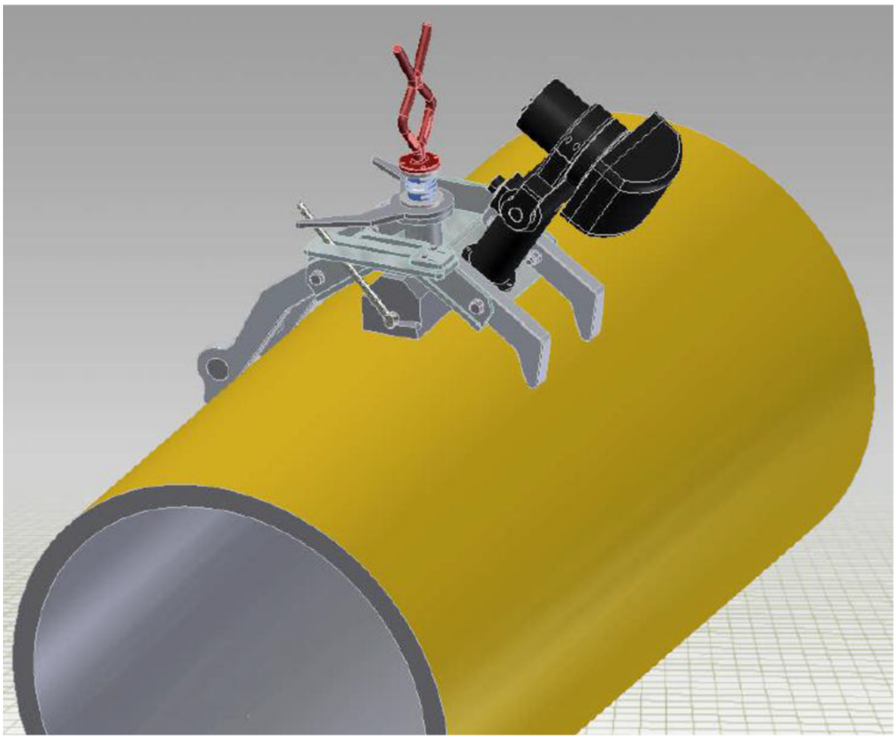

Figure 9.4: Computer generated illustration of the magnetic clamp and sonar system used to scan the Gullfaks C4 structure (image provided by ADUS DeepOcean)

9.1.1 Industry collaboration with ADUS DeepOcean

As the data had already been acquired by other contractors – the cold state by UTEC StarNet, and the hot state later by Subsea7 – ADUS DeepOcean were commissioned to undertake post-processing and visualisation of this data in an attempt to gain new insight from data which had previously been labelled as unusable.

This would prove to be particularly challenging as ADUS DeepOcean specialise in acquiring, processing and visualising high resolution survey data. As part of this project they had no input into the data acquisition, which had an impact on the quality of the data acquired. Throughout their involvement with the Gullfaks data, they had no visibility of any of the final outcomes generated by the other contractors, later discovering that the survey data had been problematic for all involved, and far from an ideal solution to the client's initial problem and aim.

9.1.2 Collaboration with 3DVisLab

The author and the 3DVisLab worked together heavily whilst post-processing the Gullfaks data. The initial problem-solving was completed through a combination of the author's knowledge of scripting and the creation of bespoke visualisation tools (a complete set of these MEL tools are provided in appendix 14.2), alongside the 3DVisLab's considerable experience of working with a wide range of problematic datasets.

As there was a limited amount of time available, and with two different 'states' of the structure in two different datasets collected by two different companies, data cleaning was divided in an effort to resolve problems and arrive at a deliverable solution in the most efficient way possible. The final analysis and comparison of the post-processed datasets were undertaken by the 3DVisLab, ready for presentation to the client by ADUS DeepOcean.

9.2 Research questions

With the research questions continuing to drive the overall direction of this research, they will be revisited below, and their relevance throughout the Gullfaks case study and how this answers them will be considered.

> **RQ0:** Can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?

Building on the work completed during the first two case studies (some of which was preparatory and therefore required to reach this point), the Gullfaks case study is a clear example of the application of 3D visualisation techniques in an attempt to 'recover' a dataset which was previously considered unusable. Whilst there is still a convincing argument for acquiring and processing data carefully and in a considered way, the Gullfaks case study shows that it is also possible to achieve results when this is not the case. It demonstrates that without using advanced 3D visualisation methods, a significant amount of time and money would have been spent on acquiring this dataset and with no tangible results.

> **RQ1:** How effective are current visualisation methods in communicating subsea survey data accurately and clearly?

The Gullfaks project applies a bespoke set of visualisation tools[64] to a problematic dataset, and in doing so, generates usable results. Although there was no opportunity for research and development into applying and comparing newer visualisation techniques (such as 3D printing), as these were not required, Gullfaks is a practical example of the strength of current processing methods when applied creatively and in new combinations.

> **RQ2:** What is the relationship between automation and 3D visualisation of subsea survey data?

As the Gullfaks data was essentially incomplete (missing GPS positioning data), automatic attempts to process this proved to be unsuccessful. In response to this, the data processing had to be completed manually, which was both challenging and time consuming. However, due to the problematic nature of the data, this seemed the most appropriate approach overall on reflection. This returns to the notion of whether particular tasks *should* be automated rather than if they *can* be (first introduced as part of the Research Themes in chapter 3).

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[64] All of the Maya tools supplied in appendix 14.2, in particular the *moveWreck*, *cleanWreck* and *exportWreck* scripts which were originally developed in response to the Gullfaks case study problems.

RQ3: What are the effects on the understanding of subsea survey data in the transitioning between digital and physical 3D representations?

As there were no physical representations of the Gullfaks data produced, it does not attempt to address this research question.

RQ4: What is the measurable value of innovation in 3D visualisation to the subsea surveying industry?

As a result of the collaborative expertise and applied tacit knowledge between the author, the 3DVisLab and ADUS DeepOcean, a complex and problematic dataset was used to generate useful results. This resulted in ADUS DeepOcean delivering a bespoke visualisation solution to a large client who had previously had two other companies fail to achieve any useful results.

9.3 Research themes

The Gullfaks case study builds upon the work completed in the first two case studies and brings the visualisation process 'full-circle', applying a variety of visualisation tools and techniques which had been used in previous projects to an example dataset which had been captured poorly, in an attempt to reclaim some value for the client.

In doing so, this case study primarily fits into three of the five research themes introduced in chapter 3 – these being **pipeline**, **value** and **data quality**.

An awareness of *pipeline* plays a significant role, as the Gullfaks dataset echoes and supports knowledge gained during the Troll case study – where the approach to the acquisition and processing of such data is equally as important as the way in which it is visualised. Although the Gullfaks project shows that results can still be generated from poorly acquired data, it highlights the significant increase in time, resources and expertise required to do so.

Value is an important theme throughout this case study – with the increase in labour required to achieve useful results (and therefore increased costs associated with this), the value of such work starts to be questioned. The increased knowledge of how to visualise data is valuable to the author, the 3DVisLab, and to ADUS DeepOcean, but ultimately, can the result still be of value to the client? In this example, the answer to such a question is yes, as it opened the doorway to further commercial work between the client and ADUS DeepOcean.

Finally, the importance of *data quality* is emphasised here – having the very best quality data available typically means that the best quality results can be achieved in the least amount of time. If the data is not of the highest quality, more time and labour are required to generate clear outputs, and being able to identify this before work commences is important in a commercial setting.

9.4 Methodology

As with the first two case studies, the research approach to Gullfaks was structured using the **Explore Review Create** framework which was introduced earlier (chapter 6). Each of these three phases would form an essential part of the creative and problem-solving processes, eventually leading to the client deliverables at the end of the project. It would also allow for an iterative self-improving process – continually re-applying new knowledge – which was essential in improving the final solutions applied to the challenging Gullfaks dataset.

During the *explore* stage, time was spent reviewing the data files received from ADUS DeepOcean. This also included looking at the incomplete results (without final conclusions or explanation) generated by two other companies which had tried to work with this data prior to ADUS DeepOcean's involvement.

After a clearer understanding of the data and what would be required was established, the author started to *review* which options would be most useful and generate the strongest results, after which the visualisation process could begin, and outputs were generated as part of the final *create* phase. The review and create stages of the methodological framework were most relevant here as the process looped and repeated itself multiple times where some practical techniques were unsuccessful. Each loop generated new knowledge which was re-applied, and would later result in the finished deliverables.

9.5 Practice

Building on the knowledge gained during the previous two case studies (Troll and Gabbard, chapters 7 and 8), the author's role in the Gullfaks project would include both processing and visualisation of subsea survey data. Processing the Gullfaks data would prove to be the most challenging phase of the creative practice. Multiple challenges were encountered throughout, forcing the author to undertake a variety of attempts in developing an approach which would generate results which were of value to the client.

9.5.1 Acquisition, processing, and visualisation

As part of the ongoing research process, the author established a simplified model for working with data, with three distinct stages – acquisition, processing and visualisation (originally introduced in section 4.5 and shown in Figure 4.5). This same model applies to work completed using the Gullfaks data, where the author's role was primarily part of the processing and visualisation stages (Figure 9.5).

Figure 9.5: Author's role in the Gullfaks project

The **Explore Review Create** framework was critical in approaching the Gullfaks datasets. As the data had been provided by another organisation, an *exploration* of the supplied data was essential – providing understanding as to the quality of the datasets, as well as the type and amount of work that would be required in later stages.

During this initial *explore* stage, it became apparent that the received data was not organised clearly, so this was the first task completed. The data provided by DeepOcean showed the towhead in its 'cold' state, with the scans completed in October 2012. After initial clean-up, there were 20 different scans, each containing 4 files – 3 different passes at varying survey angles and one file combining them. The data provided by Subsea7 contained the same 'cold' state data, and additional 'hot' state data which had been captured in April 2013. This data was labelled as either raw or registered, containing 14 different scan folders. The *registered* data files referred to a series of files where the raw data had been aligned and positioned to reconstruct the complete structure from the individual scan sections.

Data 9.1: Data repository > CS3 Gullfaks > 06 Manual Re-Alignment > FINAL_COMPARISON_v3.BIN

These files previously registered by a different company are not provided in the accompanying data repository, as the registration of the data segments was later shown to be incorrect and the file sizes were significant. However, subsampled versions were used to provide a before-and-after comparison, and are provided in the final comparison BIN file (Data 9.1).

As there was a significant amount of duplication across a number of the data files, the received datasets were then organised and consolidated (Data 9.2).

Data 9.2: Data repository > CS3 Gullfaks > 01 RAW

One of the key issues encountered during the Gullfaks project was the lack of positioning information accompanying the point cloud data. This would typically be recorded when the data is first acquired and cannot be added later – doing so would require the subsea survey to be completed again. In this instance, neither the 'hot' nor 'cold' datasets contained geospatial positioning information. Instead, each of the overlapping spherical scans were all centred around the same zero point, rather than maintaining a relative positioning to one another. This meant that, in addition to the regular data processing that would take place, each individual scan would need to be positioned and aligned in its correct location to recreate the complete structure. The original Gullfaks data (Data 9.2), in both states, was extremely dense – making the files excessive in size and difficult to work with. In addition, the point cloud data was noisy due to the amount of overlap between scan sections, and would require a significant amount of cleaning.

The *review* and *create* stages formed the majority of the Gullfaks case study, as attempts were made to resolve problems with the datasets with varying levels of success. These were evaluated, and reflection on the creative practice undertaken would inform a new or updated approach. Each variation in approach was documented, as although they may not have been appropriate in this project, the techniques used could be re-applied to other problematic datasets if required.

9.5.2 Processing approach 1: Cleaning provided 'registered' data

As the provided datasets did not contain any positional information (which would ordinarily allow for the individual scan sections to be placed relative to one another), the first considered approach to preparing the data for visualisation is to use the previously 'registered' data. That is, sections of data from a previous organisation which had already been aligned and positioned to rebuild the complete structure. Provided that this completed dataset was accurate and of sufficient quality, it would allow for the point cloud cleaning to be undertaken immediately, resulting in the quickest way of preparing the two different structure states for comparison through visualisation.

However, there were no details of how the previous organisation had aligned and positioned the scan segments, and if they were placed correctly. It was later discovered that the structure was incorrectly reconstructed and its length had been shortened considerably (ranging from 560mm to 800mm across different parts of the structure and states), though this was only realised by comparing the supplied *registered* data to the 'as-built' orthographic plans.

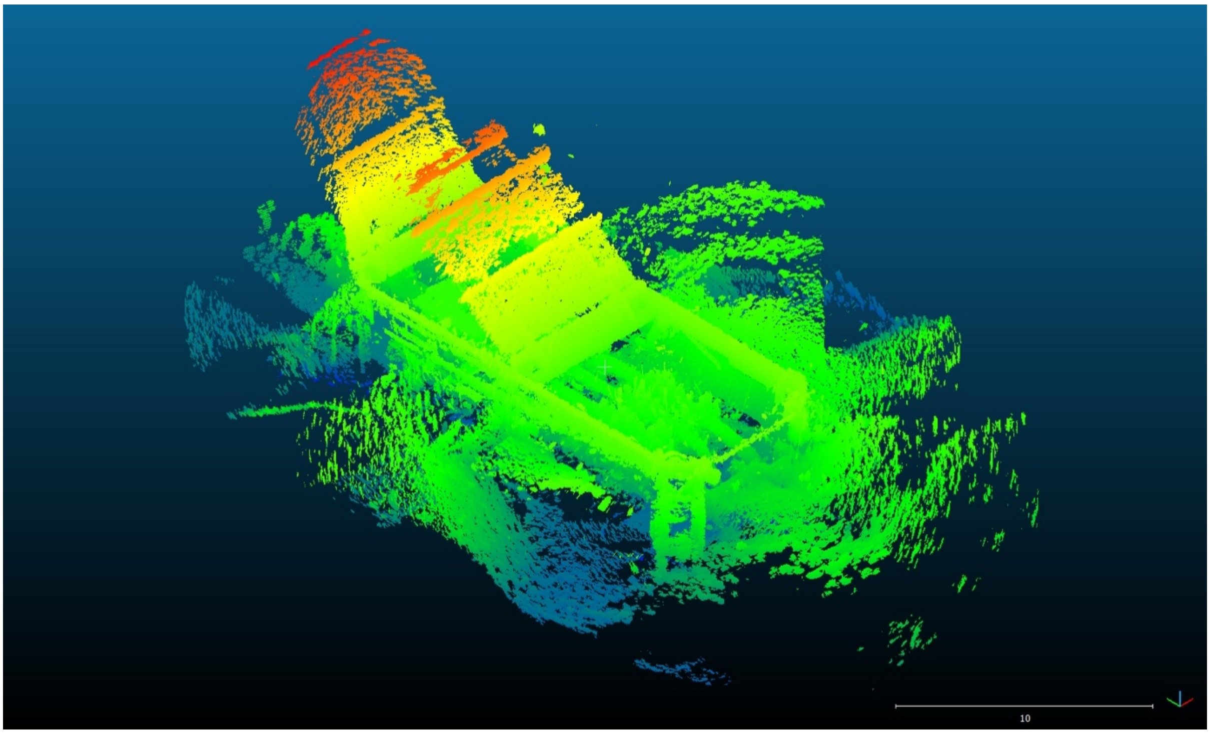

Figure 9.6: Single combined dataset, prior to processing, showing the Gullfaks towhead in its cold state

In addition, the completed structure had been saved as a single file, resulting in two point clouds which were enormous in size – the 'cold' campaign having around 59 million points, and the 'hot' campaign at around 62 million points. Figure 9.6 shows the supplied registered cold state of the structure as a single combined dataset. It is extremely difficult to identify structural features in the resulting dataset due to the density of the noise and the mismatched positioning. Additionally, the size of these datasets increased loading times significantly, making them slower to view and manage on-screen. The ability to clean noise effectively was limited, as individual scan sections blended into one another and the structure became less defined or visible. It is important to note that the huge size of these combined datasets was likely due to the amount of unnecessary overlap between the individual scan segments.

In an attempt to streamline this first approach to the Gullfaks data, a typical solution would be to sub-sample the unwieldy datasets, which would create a lighter and simpler point cloud to then finally clean and remove noise from. The ‘cold’ state point cloud was sampled using a series of values, as shown in Table 9.1.

Sampling value (minimum distance between points)	**Number of points remaining after processing**	**Percentage of original point cloud**
Original file	*59,290,363*	-
0.01	8,130,901	13.7%
0.02	3,128,944	5.3%
0.03	1,599,065	2.7%
0.05	585,765	0.9%

Table 9.1: Resulting point cloud sizes after testing different sub-sampling values

Figure 9.7 shows the comparison between the original data (left), and the 0.03 sampled data (right). The result is a much cleaner and more manageable data-set, but there is a noticeable loss of resolution, which is not an ideal solution.

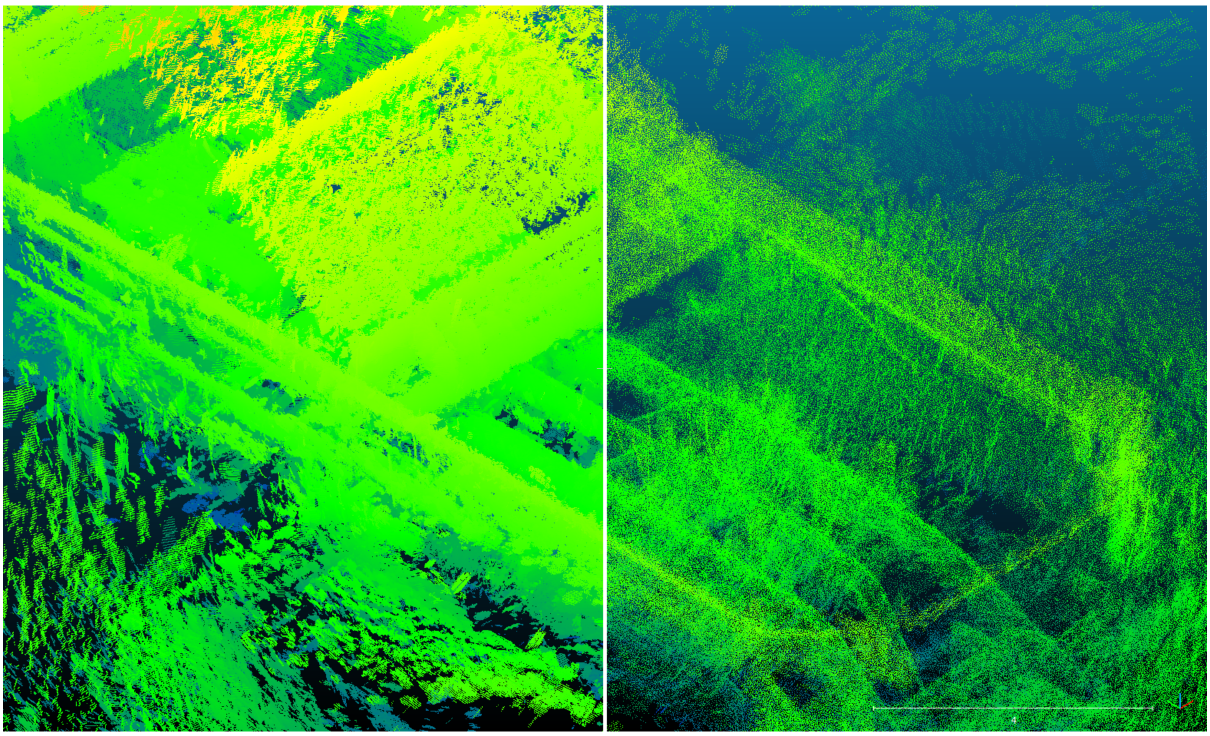

Figure 9.7: Comparison between the original and sub-sampled (0.03) Gullfaks 'cold' state

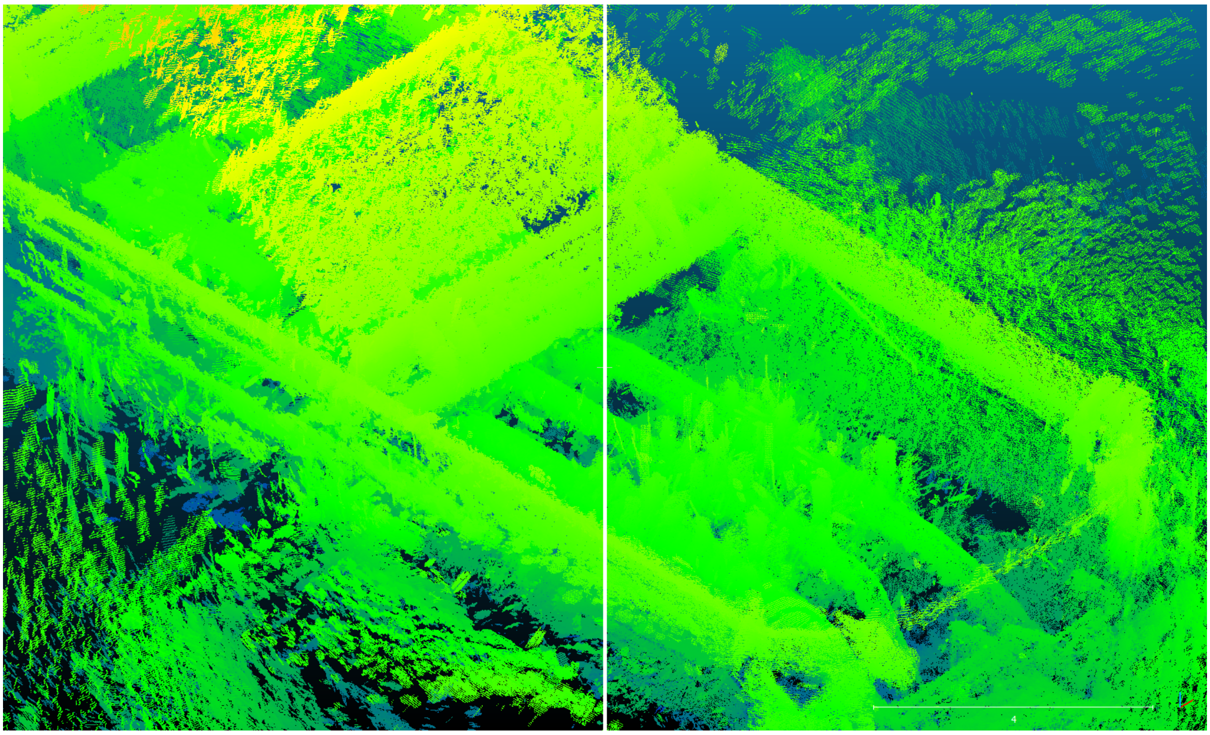

Figure 9.8: Comparison between the original and sub-sampled (0.01) Gullfaks 'cold' state (retaining 13.7% of points)

In contrast, Figure 9.8 shows the comparison between the original data and the 0.01 sampled data, with virtually no difference in resolution – but still creating a 'lighter', cleaner dataset to work with (containing around 13.7% of the original points).

After testing a range of values, a sampling distance of 0.01 proved to be optimal for this dataset, provided a compromise in retaining resolution with no noticeable loss in useful data. This also allowed for quicker processing and manipulation of the data within the software package, particularly in Autodesk Maya which had struggled with the original point cloud sizes.

However, the software algorithms used to subsample the data are unable to distinguish between useful data and unwanted noise, and instead remove points uniformly. This means that 'good' points are also lost unnecessarily, and that the remaining points still require further manual cleaning.

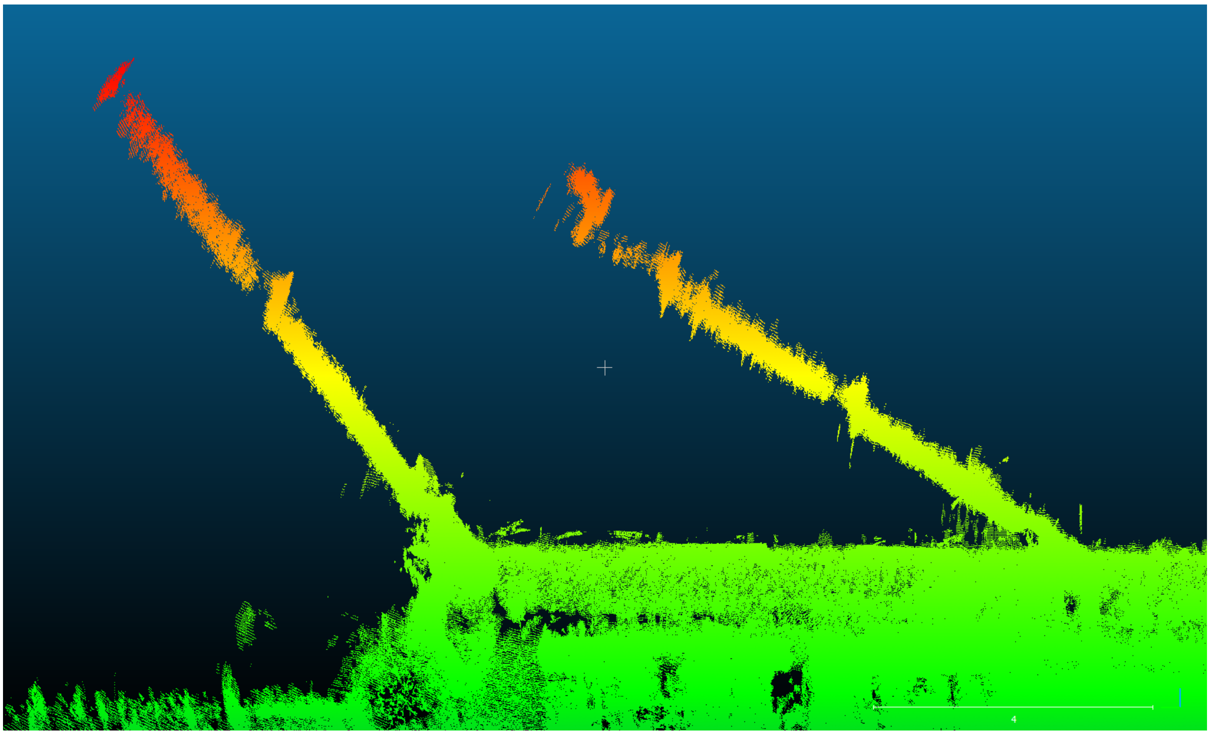

Figure 9.9: Example of edge 'feathering' seen in the supplied registered Gullfaks dataset

Figure 9.9 shows the level of noise present in the sub-sampled version of the data. A particular problem in the Gullfaks datasets is the distinct 'feathering' on all of the edges – where these are not clearly defined and need to be interpreted rather than viewed. Based on previous experience, correcting this would require a significant amount of manual cleaning, likely measurable in weeks rather than days or hours.

Due to the significant time investment, which would yield less than ideal results (cleaning an already poor dataset), this approach to processing the Gullfaks data for visualisation and comparison was not recommended and it was agreed that alternative approaches should be considered.

However, the practical experience gained – understanding when to use sub-sampling and how to achieve this effectively – in testing sub-sampling would still be of value to both the 3DVisLab and ADUS DeepOcean, as this could be later re-applied to the Gullfaks data, or even applied to datasets of a better quality which needed to be reduced in size.

9.5.3 Processing approach 2: Automatically aligning individual scans

As the supplied registered data was shown to be incorrectly re-constructed, and therefore inaccurate and unusable, the next suggested approach was to consider how the author could undertake the task of re-construction in-house ensuring that individual scan sections were placed correctly. This would form another iterative improvement of the working processes already undertaken, where the knowledge gained during the first approach would be used to inform the next. This highlights the importance of the author's *review* and *create* stages of the methodological framework being used to structure and develop the practical research component.

In manually recreating the Gullfaks structure correctly, there would also be the opportunity to maintain the individual scan sections as part of the complete structure. This would then allow for greater control whilst cleaning the data as each section could be isolated. This proved to be the most useful method of managing data built from multiple scans, as discovered during the data processing undertaken during the Greater Gabbard case study (section 8.5.2).

Based on the author's fieldwork experience, good surveying practice would ordinarily record positioning information alongside the survey data being acquired. Having this would allow the chosen software package (such as CloudCompare) to position and align the individual scan segments relative to one another, creating a complete structure. This would effectively be automatic, and so the only drawback would be in having to load each of the individual segments, and the additional time this would take (usually measurable in minutes, rather than hours or longer).

However, as the provided data was not acquired by ADUS DeepOcean and was missing this critical information, there was no guarantee that this would be possible, and so the individual scans had to be inspected to see how they aligned when loaded simultaneously. In this instance, each scan segment had been reset to centre around the same ‘zero point’ (origin) – effectively overlapping the position of the sonar head in each scan, despite the real-world placement being different. In addition, loading each of the individual sections together did not create a single recognisable structure. Figure 9.10 shows an example of this, with the first cold state scan position shown in red and a second scan in green, and where neither scan correctly overlays the completed structure or the other scan. The correctly re-built structure (achieved later during this project) is shown in greyscale, highlighting the significant differences in both alignment and rotation.

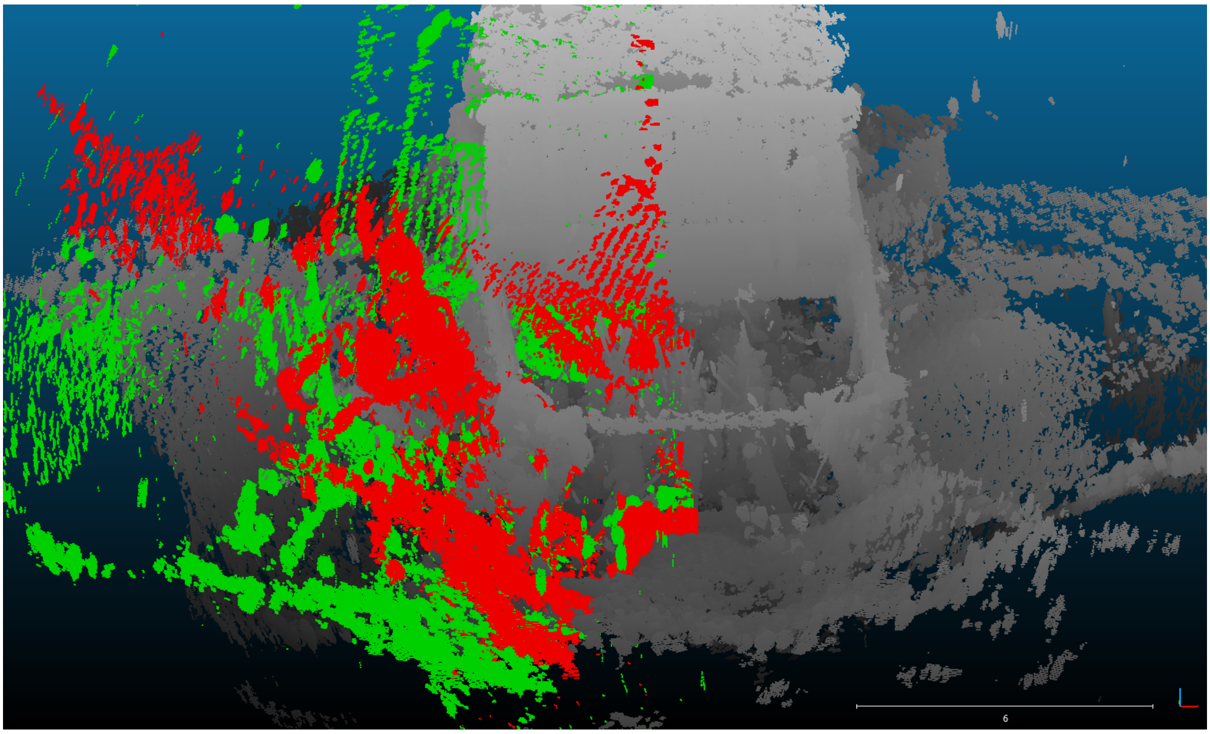

Figure 9.10: Original scan placement (red/green) shown against the corrected and complete structure (grey)

As a result of this exploration towards a new workable approach, it was realised that there would be no way to automatically re-create the completed structure from the individual scan segments, and these would have to be manually aligned and positioned. This would be undertaken using the as-built plans provided, and by comparing the placement of known fixed elements.

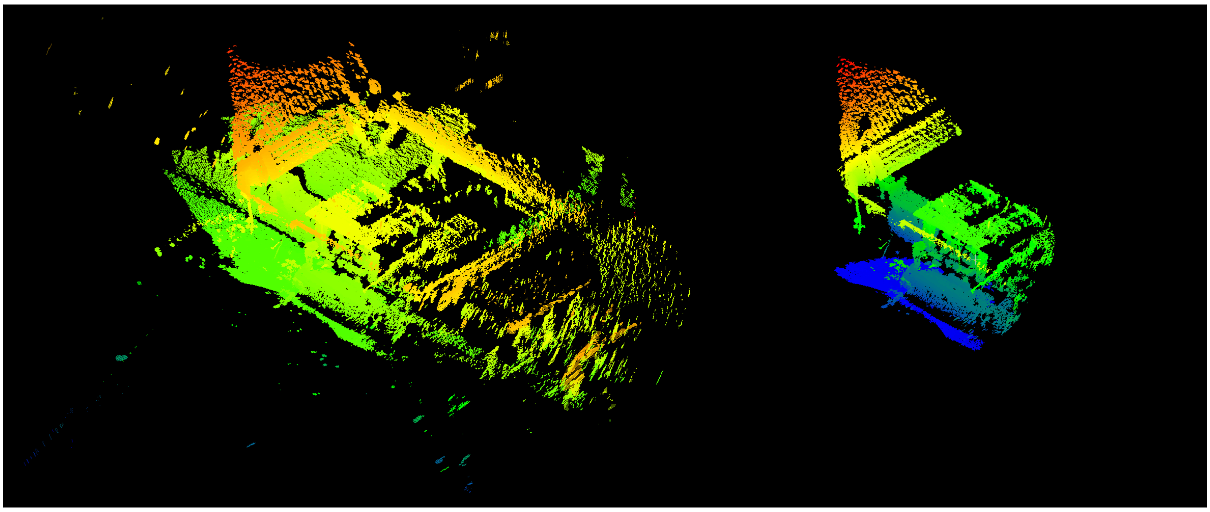

Figure 9.11: A single scan of the Gullfaks hot state, showing raw and un-processed data (left) compared to the final version of the same scan (right, as processed by the author and the 3DVisLab)

In addition to requiring manual re-construction, each of the individual scan segments were still extremely dense (Figure 9.11) and sometimes not clearly defined (as was also discovered with the registered data during Approach 1 in section 9.5.2). The combination of both of these problems created a challenging and unique dataset, and it became clearer as to why the previous organisations had struggled to generate useful results before the involvement from ADUS DeepOcean and the 3DVisLab.

9.5.4 Processing approach 3: Align, clean, combine

As discovered during the previous two approaches to the Gullfaks datasets, each individual scan section needs to be positioned correctly and cleaned, or at the very least, simplified and readied for further processing. As there are significant areas of overlap between each of the scan sections, a more typical method of undertaking cleaning is to clean each of the scans individually before combining them – allowing smaller amounts of noise to be removed before the resulting dataset grows in volume and becomes unmanageable (as found with the first approach using the registered data in section 9.5.2).

However, as these scan sections are not correctly positioned, removing point cloud data as part of cleaning can potentially make it more difficult to align sections with the others. This is because any overlap is essential in manually placing a section relative to the others, allowing the data processor the best opportunity to identify fixed locations which match. As a result, the third approach consists of three main stages – aligning the scan sections (whilst ensuring each one is kept separate from the others), cleaning the data on a per section basis, and finally, combining the resulting aligned and cleaned sections to create a single finished dataset, ready for visualisation.

The following sub-sections introduce the key tasks which were proposed as part of Approach 3, with the following section (9.5.5) detailing the results of undertaking each of these once the author's approach had been agreed upon with the 3DVisLab and ADUS DeepOcean.

9.5.4.1 Aligning scans and recording offsets

Having been given a complete registered point cloud, and all of the scan sections it had been created from, the complete model can be used as a 'map' to manually align and position these individual scans, recreating a complete version of the structure whilst maintaining separate scans which would later be invaluable during cleaning.

Using a combination of 3D modeling packages (Maya and CloudCompare) paired with custom built proprietary software tools (in particular, the author's *loadWreck* scripts, found in appendix 14.2), each scan would be loaded individually, alongside the complete dataset that it partly represents. Each section could be manually moved and rotated in three-dimensions, and using point-snapping tools, the exact overlap could be found, revealing its positional and rotational offsets.

Once these offsets have been found, new versions of the XYZ data files can be exported, which reflect the updated positions and rotations of each scan section. This means that the new XYZ files can simply be reloaded and each scan section will already be in its updated position, creating a complete version of the Gullfaks structure – something which Approach 2 (section 9.5.3) had hoped to start with.

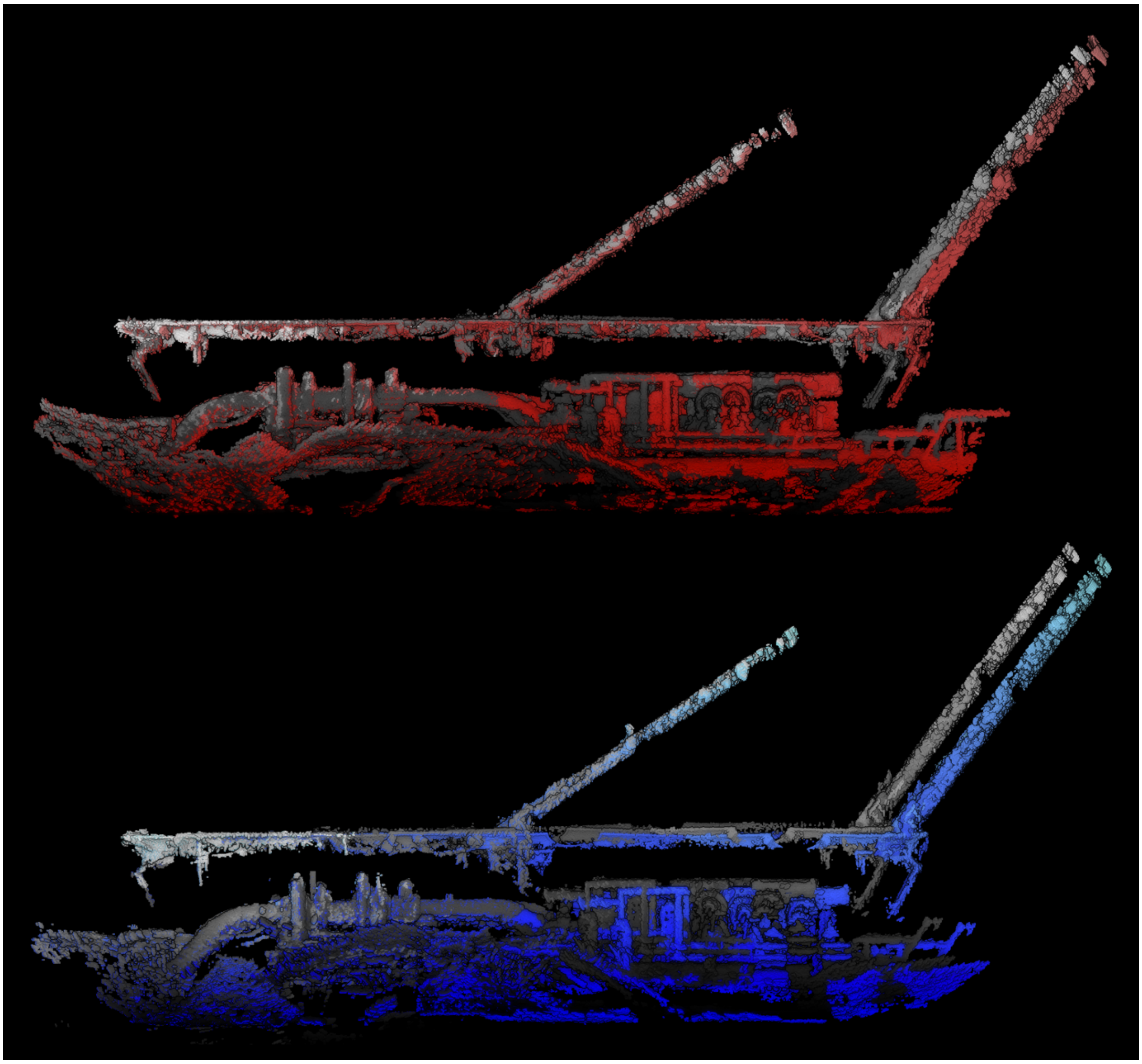

Figure 9.12: Correctly reconstructed hot and cold states (red and blue, respectively) of the Gullfaks C4 structure compared to each of the originally provided datasets (grey) – the largest reconstruction errors can be seen on the right-hand side of each state

It is important to note that the incorrect shortening of the structure in the supplied registered data had not been realised until this stage of the various approaches. The registered dataset was used to align individual sections, and then finally compared to the as-built plans, which in turn revealed the placement errors along one axis. This can be seen in Figure 9.12 and was a critical discovery, as the errors were encountered along the same axis in which the change between hot and cold states was to be measured.

Although aligning the sections manually would prove to be a time-consuming task, it was now essential in creating a complete and accurately aligned finished dataset.

9.5.4.2 Cleaning data

Once the offsets have been calculated, data cleaning can then take place. For this approach, it was intended to contain two separate stages, undertaken on a per-scan basis.

As first discovered using BlueView sonar data during the Troll project (section 7.5.1), Gullfaks also had a significant amount of overlap between each of the near-spherical scan segments. The accuracy of the data also lessened across points further from the 'zero point; (i.e. the position of the sonar device during each 360° scan). As a result, the first stage of cleaning would involve trimming data from each scan section beyond an acceptable range. This acceptable range was chosen so as to remove as much overlap between scan sections as possible whilst not creating gaps in the completed structure. This would result in a series of smaller scan sections that would each provide the best quality data for its own position, and would therefore not be obscured by a less accurate piece of point cloud data. In this instance, data points beyond six metres from the origin of each scan section was removed.

Once this data 'drop-off' has been completed, the next stage of cleaning is to manually remove any remaining obvious noise. Although likely to be time-consuming, it would be much quicker to undertake this cleaning on a per-scan basis. This stops larger areas of point cloud noise being created when aligned scans are combined, where the additional visual clutter can make these difficult to clean.

9.5.4.3 Combining data

Once each scan has had its offsets calculated, and has had most of its poor data and noise removed, the individual scans can be combined. These will all align correctly, based on the offsets calculated earlier, allowing the full structure to be recreated whilst maintaining each individual scan section. At this stage, a final pass of cleaning can be undertaken if necessary. Once the data has been reconstructed and cleaned, it will be ready for further visualisation and to explore the best way of presenting the results to the project client.

9.5.5 Results of using processing approach 3

Having developed a suitable approach to processing and visualising the challenging and problematic Gullfaks datasets, this was then applied and undertaken. The following sections compare the process as planned to the process as applied, highlighting the parts which worked and any new problems which were only encountered once the process became 'real'. This reinforces the importance of a real-world research environment, as first discussed in section 6.1.7, and forming a contributory part of the **Explore Review Create** methodology.

9.5.5.1 Aligning scans and recording offsets

First attempts to calculate the positional and rotational offsets were undertaken using CloudCompare. Unfortunately, this software package does not include controls for easily and visibly fine-tuning these attributes and was therefore unsuitable for this type of task.

Instead, Maya was used to complete this part of the process. With no other data loading means available, this required the use of the author's *loadWreck* tool (appendix 14.2.1), allowing for the data to be initially loaded; once it was, the standard object manipulation tools (in particular, *translate* and *rotate*) in Maya offered a precise method of aligning point cloud sections. Maya also offered the exact numerical offset of each point cloud object[65], so that these could be finely adjusted, or recorded and re-used later if necessary.

It was during this part of the process, however, that differences in the structure length were highlighted in the two provided versions of the 'cold' state data – one set of files from each of the two previous organisations that had worked with the Gullfaks datasets. To check if one of these *had* been scaled, one section of each version was first manually aligned with the full and registered dataset for comparison.

As the recorded points in each version should be identical, any change in scale would be easily identified visually. To make this as apparent as possible, matching points at one end of the data sections were aligned and treated as fixed anchor points, and then matching points at the opposite end were aligned as closely as possible, with the result showing any offset or changes in scale or rotation.

Figure 9.13 shows the three data sets anchored to one shared point (marked with the yellow box). The red data points represent the incorrect version, whilst the blue points are the matching and aligned dataset. The grey data is an extract from the complete model used for comparing placement. If the two sets of cold state point clouds were identical, the red and blue points would exactly overlap.

Figure 9.14 shows the alignment of the opposite corner (where the largest angular offset from the fixed anchor point will occur), with the blue data matching the grey. This also further highlights the distance by which the red dataset is different. As the Gullfaks project objective was to correctly identify measurable differences between two states of a subsea structure, any scaling of the point cloud data would have an

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[65] In Maya, each loaded point cloud is treated as a single particle object, containing a number of particles where each represents a single point cloud data point.

immediate and negative impact on the accuracy and validity of any measurement or comparison.

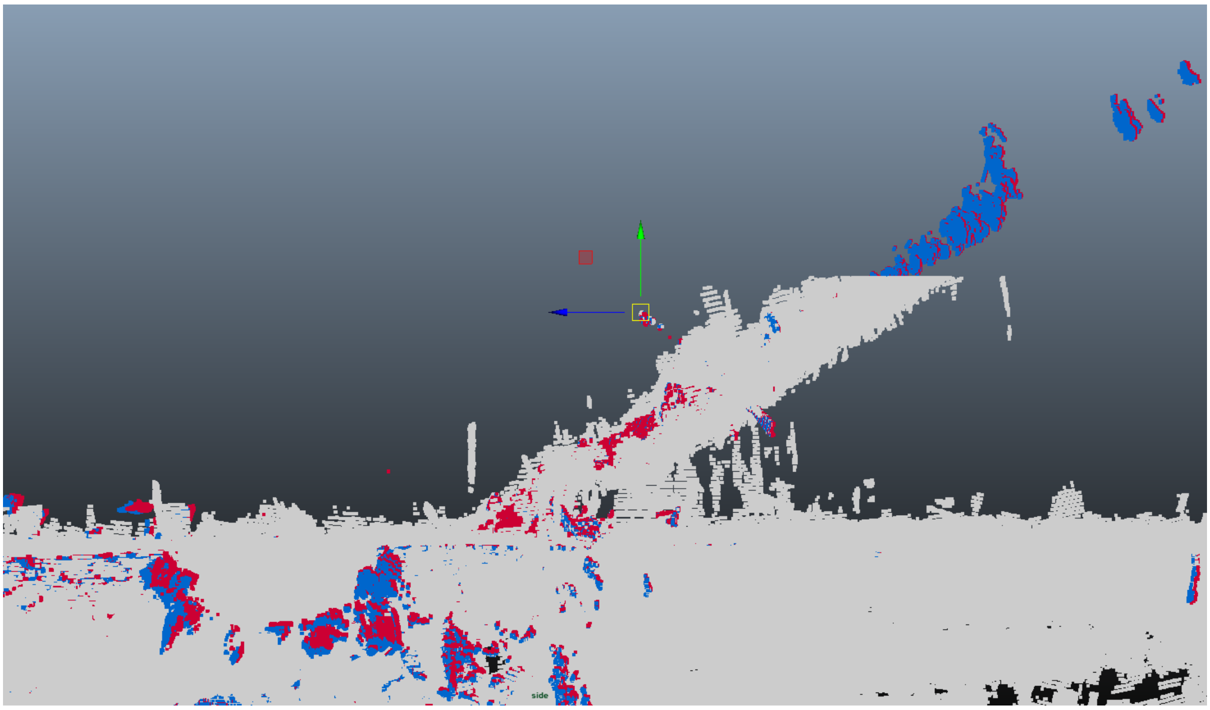

Figure 9.13: Comparison of each version of the Gullfaks 'cold' data, showing misalignment in one version

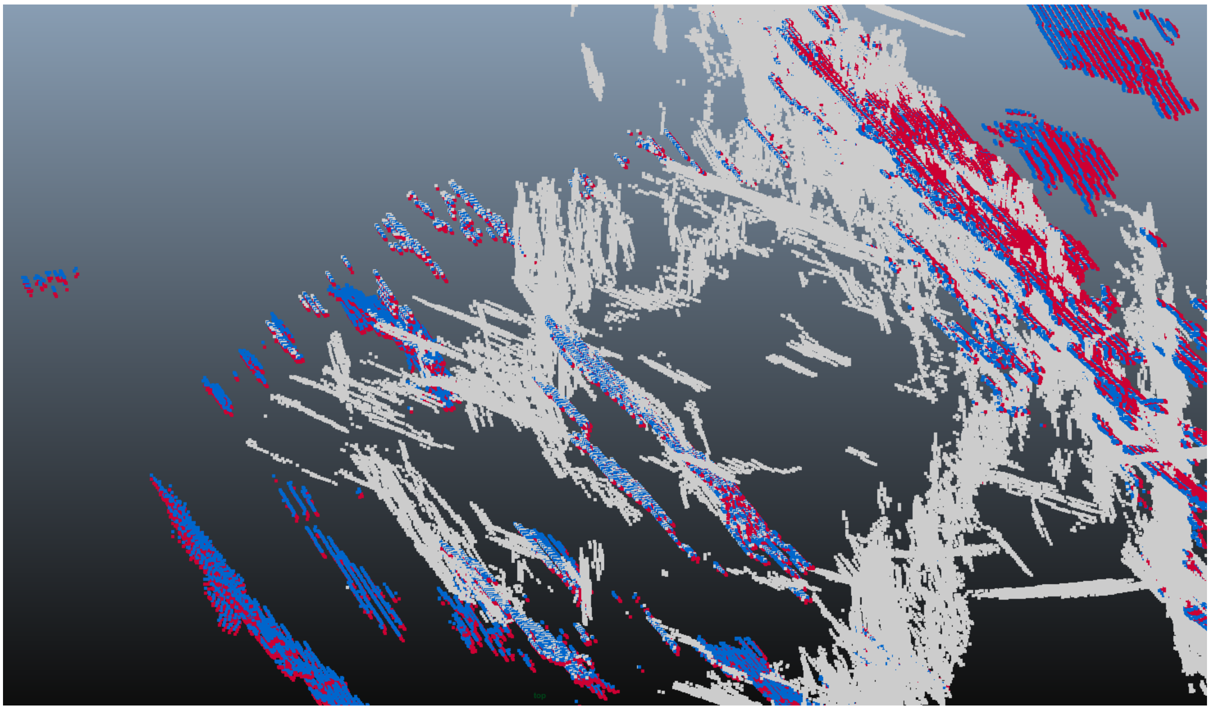

Figure 9.14: Comparison of each version of the Gullfaks 'cold' data, showing misalignment in one version (shown in red)

Having identified the differences – which were not initially evident – it was agreed with both ADUS DeepOcean and the 3DVisLab that in an effort to maintain data accuracy (though already limited across the Gullfaks datasets) and minimise or remove any contribution to margin of error, the unnecessarily scaled version of the cold data would no longer be used. Using the remaining set of cold state scan data (Data 9.2), each individual scan segment was manually aligned and positioned correctly (primarily relying on Mayas *translate* and *rotate* tools), creating a complete and recognisable structure. This is not a technically complex process, but requires both patience and precision, and is time-consuming to complete to a high standard. After manual alignment has been completed, the data is ready to be exported out of Maya as a set of new and aligned XYZ files which can then be used throughout the rest of the processing and visualisation stages.

9.5.5.2 Exporting aligned data

There were some unexpected difficulties in exporting the aligned data once it had been completed. The resolution of these problems is documented in this section, requiring four different attempts to address the issues encountered when exporting data. This reinforces the importance of the author's application of an iterative process of improvement based upon action research. The successfully exported aligned data files are provided in the accompanying data repository (Data 9.3)[66].

[66] The files provided in Data 9.3 can be compared with those in Data 9.2 on a 'like for like' basis, showing the significant differences between the original datasets which are unaligned and those which have been manually aligned and corrected (section 9.5.4.1).

Data 9.3: Data repository > CS3 Gullfaks > 02 Aligned Files

Attempt 1: Using Maya 2015 to import, align and export

In the first attempt, Maya 2015 was used throughout the entire process – to import, align and then export the individually aligned data sections.

Data files were successfully loaded using either the existing WreckSight plugins provided by the 3DVisLab, or by using the author's *loadWreck* MEL script (appendix 14.2.1) which is also able to quickly load point cloud text files into Maya. As mentioned previously, once a data file is loaded, Maya offers the ability to precisely fine-tune both positional and rotational values of each individual scan to correct its alignment as part of a completed overall structure.

However, as the WreckSight plugins were compiled for Maya 2011, some of the included features were no longer fully functional – including the option of 'baking'[67] or confirming the updated point cloud positions[68]. Without baking, the plugin's limitations would result in Maya ignoring the updated positions and only exporting

[67] In computer graphics, *baking* refers to a process used to consolidate a system of data (such as textures, attributes or simulation values) into a simplified, more permanent form.

[68] A scripted solution was later developed by the author to recreate this functionality (appendix 14.2.5) after the Gullfaks project had been delivered and time was no longer critical.

the local/original coordinates[69]. As a result, using the WreckSight plugins with Maya 2015 was useful only for importing and aligning scan sections, whilst being unable to export them.

Attempt 2: Testing import, align and export in Maya 2011

In response to the WreckSight plugin issues whilst using Maya 2015, Maya 2011 was tested as an alternative. Maya 2011 could be used to load data using the original WreckSight plugin, or by using the author's MEL script which is not restricted to a specific software version. Maya 2011 also offers the same type of alignment control as Maya 2015, and on a small test dataset (of 10 points), the fully functional WreckSight plugins could be used to successfully export datasets in their updated positions.

However, despite being able to undertake each of the steps required during testing (using a small dataset), Maya 2011 was not capable of handling the volume of points necessary (around 11 million in total) when aligning large datasets. This included frequent software freezes/crashes and a significant impact on performance, stopping any data processing from being possible. Due to this, using *only* Maya 2011 would be not be viable.

Attempt 3: Editing in Maya 2015, then moving to Maya 2011 for export

As Maya 2015 and Maya 2011 can each perform different parts of the process, one potential solution was to therefore incorporate them both as required. Maya 2015 could be used to import and align the individual point clouds, and then these scene files can be opened correctly in Maya 2011 with no noticeable problems, to be

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[69] This is because any updated offsets are applied to the Maya particle object, and not the particles within (which maintain a relative positioning to the object position).

exported. However, despite not being required to undertake any manual processing, Maya 2011 still could not comfortably handle the sheer volume of points being loaded.

Consequently, exporting an updated data file from Maya 2011 took a significant amount of time – with the export process for a complete set of files taking more than one full working day. This is because the faster MEL exporting function would only export the local or relative position of the point cloud data – that is, the position of each point *before* it was aligned correctly – and could not be used. In order to export the updated coordinates, the WreckSight plugin had to first be used to 'bake' or confirm the new positions, which could then be exported using the original WreckSight plugin (and this could only be completed using Maya 2011 with smaller datasets). As a result, this approach to aligning and exporting the data was deemed unsuitable due to the estimated duration to complete.

Attempt 4: Testing new methods of exporting in Maya 2015

With previous attempts showing Maya 2015 was the most successful means of handling large point clouds, further experimentation with the built-in particle exporting feature was undertaken[70]. Instead of querying the local position of each point in a larger point cloud (the default approach), it was discovered that the updated *world position* of each point could instead be queried – this would return the updated position of each point after a scan section had been aligned. Knowing this was possible, each individual scan could then be imported, aligned and exported using Maya 2015 exclusively.

[70] This refers to the *dynExport* MEL command, which can be used to output particle data in a customisable and editable ASCII format.

In addition, each of these processing tasks could now be completed using scripted MEL commands, which would not be tied to a particular software version – a distinct advantage over using the WreckSight plugin which had previously been used for these types of tasks.

9.5.5.3 *Automatically cleaning data*

In addition to Maya 2015 being able to import, align and export the data, some automatic data cleaning would also be required, and in practice this would happen as part of these initial processing stages.

In an attempt to minimise the accumulation of noise and inclusion of poor data, experienced members of the 3DVisLab suggested that all data beyond *X* metres be automatically removed from each individual scan before being manually cleaned and aligned. Upon further inspection of the data, and due to the awkward scan positioning, an optimal distance of six metres was chosen.

This section describes several attempts undertaken by the author to achieve the automation of this processing task. The resulting automatically cleaned data files are provided in the data repository (Data 9.4) and can be directly compared with those used at the start of this stage (Data 9.3: Data repository > CS3 Gullfaks > 02 Aligned Files).

Data 9.4: Data repository > CS3 Gullfaks > 03 Aligned Files (6m)

Attempt 1: Recreating point cloud based on distance from zero

As the other stages were being completed in Maya 2015, it was essential that this data drop-off would also form part of that software pipeline. The initial attempt took place after a scan segment had been imported and manually aligned, but before the new position had been baked for exporting.

A custom-built MEL script (*cleanWreck*, provided in appendix 14.2.6) was developed which would evaluate a point cloud on a per-point basis. Calculating each point's distance from the point cloud's zero origin, using Equation 9.1, would allow for the length of a straight line in three-dimensions to be calculated. In this instance, a distance of six metres was chosen – if a point is greater than six metres from the origin, it will not be recreated.

$$\sqrt{(x^2 + y^2 + z^2)}$$

Equation 9.1: Length of a straight line in three-dimensions (where the origin is zero)

This method relies on querying the *local position* of each particle (its original position before manual alignment and offset, when the point clouds origin was zero), then using the particle's *world position* to create a new one in the correct updated position. Initial testing was successful, but showed particle creation to be around ten times slower than particle evaluation. Further exploration of this issue showed Maya querying a particle's *world position* was the cause. As a result, this approach would take several hours to complete just one of the 33 data files.

Attempt 2: Avoiding *world position*

Similar to the first attempt, but instead of recreating particles using their *world position*, the MEL script was edited to recreate a new 'trimmed' point cloud in the original local position. Each data file was processed in around 10-12 minutes, proving to be significantly faster than attempt 1, but with noticeably less overlapping data available to aid in manually positioning and rotating the scan section into the correct position.

Attempt 3: Manually writing files

Building on the previous attempts, which used the built-in Maya exporter once the data had been trimmed beyond six metres, this attempt would instead rely on additional scripting to create a new tool[71] which could export data in the most basic format possible (a text file with one set of XYZ coordinates per line). Unfortunately, this did not improve processing time, which confirmed that the particle creation step was responsible for the increased delays.

Attempt 4: No longer recreating the particles

In response to the realisation that creating particles was adding unnecessary processing time, this attempt would entirely remove that particular element of the process. Each scan segment would still be imported and manually aligned, but then the new offset origin would be used to process the *original text file* for the six-metre threshold, as opposed to evaluating and creating points in the 3D particle system in Maya. As the origin of each data section would no longer be zero, Equation 9.2 was used.

$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Equation 9.2: Length of a straight line in three-dimensions

In this version of the MEL script (*exportWreck*, provided in appendix 14.2.7), points would be read from the original text-based data file, where each line represents a

[71] This tool is not supplied in the appendices as it was combined with elements of the *cleanWreck* script during the creation of the updated *exportWreck* MEL tool.

coordinate with *x*, *y* and *z* values. For points which are less than six-metres from their scanning origin, these would instead be written into a new text file and would represent the updated and aligned position of the point cloud. As no particles were being recreated, and Maya is simply a vessel for processing a text file, this approach was significantly faster than the others with processing time under one minute per file (compared to several hours for each file, as in the first attempt).

9.5.5.4 Manually cleaning data

After the first phase of cleaning was completed automatically (using the MEL script to 'drop' data points beyond a specified distance from the scan location), manual cleaning on the remaining points could be undertaken. Prior to undertaking manual cleaning, each of the XYZ file groups were combined into single CloudCompare BIN files, ensuring that all related scans would remain together and that file-sharing between team members would be simplified (Data 9.5).

Data 9.5: Data repository > CS3 Gullfaks > 04 BIN Files

Manual cleaning was undertaken by both the author and the 3DVisLab. The cleaned 'hot' state BIN file (completed by the author) can be found in the data repository (Data 9.6). For comparison purposes, this BIN file also contains the points which were removed during manual cleaning – these are visible by default, though can be hidden from view. There were no further issues throughout the manual cleaning stage, and this was completed in a similar manner to that already undertaken in case study two, Gabbard (section 8.5.2).

Data 9.6: Data repository > CS3 Gullfaks > 05 Manual Cleaning > hot_combined_6m_subsampled_WIP.BIN

9.5.5.5 Combining finished data sections

As the data problems had been resolved during the earlier phases of processing, combining the scan sections uncovered no further issues. After each individual data file had been correctly aligned and fully cleaned, the completed file sets (one for each state – hot and cold) could be reloaded simultaneously alongside the other, creating one larger finished dataset for inspection and analysis, or for further visualisation. The final set of Gullfaks data files, which were used to present results to the client, can be found in the data repository folder (Data 9.7). This folder also contains Maya files and images which were used to identify and correct any discrepancies in the object construction (including the previously noted shortening along one axis).

Data 9.7: Data repository > CS3 Gullfaks > 06 Manual Re-Alignment

9.5.5.6 Summary

Having encountered and resolved a series of challenging issues whilst processing the Gullfaks dataset, the practice-led research undertaken as part of this case study resulted in a greater knowledge and understanding of processing problematic point cloud data effectively. Although many of the issues were encountered as part of this single dataset, the techniques used to resolve these issues can be re-applied as required.

Throughout the Gullfaks processing, a clear rationale for the final approach was developed. Maya 2015 was used exclusively, as Maya 2011 could not cope with the size of the point cloud data files. Using a single 3D software package also eliminated the possibility of errors while transitioning between programs. There was never a need to load data files more than once, significantly reducing waiting times during processing. Finally, using the built-in Maya data exporter alongside new custom-built scripting tools removed the need to recreate point clouds using the previously used WreckSight plugin.

Upon completion, a selection of scripted tools had been created and replaced the need for WreckSight plugins that were previously tied to specific software versions. The Gullfaks data processing consisted of the following key steps:

- Import individual scan to Maya using custom data loading script.
- Fine-tune position and rotation of the individual scan against a portion of the completed dataset.
- Export a new data file from Maya using a custom MEL exporter script, ready for cleaning.
- Use the newly exported file and the custom data-trimming script to remove points six metres from the scan 'zero' position.
- Undertake additional manual clean-up of points if necessary.
- Repeat each of the above steps for all scan sections, and then combine all of the completed sections into a single dataset using CloudCompare.

By developing this processing pipeline, usable results were generated in the most efficient manner possible with significant speed improvements being achieved throughout the process. In addition, the causes of any processing delays were clearly identified so that these could be avoided in future projects.

9.6 Findings and reflection

As the third and final case study, Gullfaks played a key role in combining knowledge and understanding gained by the author whilst working on the Troll (chapter 7) and Gabbard (chapter 8) case studies, with additional practical skills and problem-solving techniques. The varying approaches being developed and tested were structured using the **Explore Review Create** methodology (introduced in chapter 6) and relied on a cyclic process of improvement and iteration, leading to complete and usable solutions.

The Gullfaks case study created an opportunity for the author, 3DVisLab and ADUS DeepOcean to work with a problematic dataset that had been poorly acquired. As there was not an opportunity to capture the survey data again, this constantly improving expertise in both data processing and visualisation techniques would prove to be highly relevant throughout this commercial project.

As detailed throughout the case study three practice (section 9.5), a variety of approaches and attempts were made to resolve the identified data issues. Although the final solution for the Gullfaks data did not incorporate all of these, each one contributes to an existing and evolving collection of processing and visualisation tools and techniques which can be re-applied to alternative datasets if required. The most useful of these by far is the ability to recreate all of the existing WreckSight plugins in a manner which no longer ties them to a specific version of Maya, as it was discovered that earlier versions are less suited to handling larger volumes of point cloud data.

Upon completion of the project, ADUS DeepOcean presented to the client and suggested that clearer results (that is, those which would provide a more accurate means of comparing the hot and cold states of the structure being surveyed) could be achieved in a more efficient manner had they been involved throughout the entire process, most importantly during data acquisition. If ADUS DeepOcean had been responsible for acquiring the Gullfaks datasets, where each of the scan segments would have had accurate positioning information, there would have been no need to correct the position or rotation of each of these point clouds which was a time-consuming and somewhat interpretative task. There also would have been no significant placement errors in the reconstruction of the completed structure as this problem was originally present due to human error, and a misunderstanding of the structure being observed in the data. However, there would also have been no requirement to further explore more advanced ways of outputting data beyond those already provided by the WreckSight plugin, and so the processing pipeline may still have been seated in an earlier version of Maya.

This all-inclusive approach (one which considers acquisition, processing and visualisation and ensures the pipeline benefits each of these) builds on the knowledge generated by the author during the first two case studies where a strong understanding of the entire working process heavily influenced its final outcomes, and potential problems were more easily be avoided. The other companies which acquired the Gullfaks data had excluded the gathering of positional information, something which would have critically changed the success and outcome of the project had they considered the impact and importance of such information in the later stages of the data lifecycle.

Finally, as also realised during the Gabbard case study (discussed in section 8.5.5) the Gullfaks dataset would have benefitted from a data grading scheme where potential outcome quality and the time taken to achieve this could be estimated before work began. This would provide a clearer indication as to the viability of the data, and whether the expectations of the client could be feasibly met or should be adjusted. Such a data grading system could include a checklist of required or desirable data attributes, and in this instance not including positioning information as part of the point cloud data files would encourage the data to be re-acquired, or provide a rationale for why any outcomes may not be optimal.

However, had a data grading system been used to evaluate the Gullfaks dataset, it is entirely possible that this further developmental visualisation work would not have been undertaken. After approximately two years without any useful results, the client had almost given up on the data being of value. It was only through the shared and applied knowledge of the author, 3DVisLab and ADUS DeepOcean that a bespoke solution was created – though one that was with a higher margin of error than initially requested.

Although a positive outcome had been achieved, starting the project with a high-quality dataset (and one which also included accurate positioning information) could have led to simpler and faster data processing, resulting in cleaner and more accurate results. These results would have allowed the client to measure the differences between the hot and cold stages of the Gullfaks towhead with a lower margin of error than that of the actual datasets provided.

9.7 Future work

One of the key areas identified during these practical case studies is the creation and application of a data grading system for subsea survey data.

Discussed in more detail in section 8.5.5 (and again in section 9.6), such a system would have been of great benefit during the Gullfaks research and practice. Creating a data grading system for visualisation (similar to the one ADUS DeepOcean uses for acquisition) would prove to be a useful addition in estimating timescales and outcome quality before any work commences.

Fully developing such a system would require a significant amount of evaluation of subsea survey data to identify common factors, and would benefit from a series of interviews (or similar) with industry professionals to help clearly define criteria, requirements and expectations. As such, this task lies beyond the original scope of this research and could form part of future work for the author, perhaps in collaboration with the 3DVisLab or ADUS DeepOcean.

However, a fourth and final research chapter (chapter 10) proposes an initial data grading scale created by the author, built on the knowledge gained throughout of the previous three case studies. This offers a developmental system for evaluating subsea survey data gathered using multibeam sonar, and acts as a starting point for improving data capture and quality awareness when visualising this type of data.

10 Creating a Data Grading Scale

This chapter discusses the creation of a data grading scale suitable for multibeam survey data – the *Dundee Data Grading Scale* (or *Dundee Scale* for short). This grading scale is built upon the knowledge and understanding developed throughout each of the three practical case studies undertaken by the author, and the rationale for this has been developed as part of the contextual review and commercial practice.

The following sections will introduce a series of existing measurement and scale systems before highlighting common elements which contributed to the creation of a draft data grading scale, originally titled the Gauld Star Scale. Further development resulted in the iterated (and retitled) Dundee Scale as a proposal and first step towards improving data acquisition and awareness of quality in this challenging data domain. The first versions were evaluated by the author, with reflection on practice informing the design choices and development alongside the exploration of other grading scales and systems (examples of these are provided in appendix 14.5). The most recent presented version of the grading scale (Figure 10.6) was evaluated by industry experts using online interviews (appendix 14.4).

It is important to note that the resulting Dundee Scale is presented as an original and draft proposal. The author recognises that as no similar work has been undertaken previously, fully realising such a grading scale is a significant body of work, one which exists beyond the original scope and focus of this research. As such, this could form part of future work, and would include further development of the scale. In particular, this would include a more exhaustive application and evaluation across a wider variety of datasets and subsea survey types (for example, laser survey data).

Finally, this research continues to be structured using the author's **Explore Review Create** methodology, introduced in chapter 6 (an extract is shown in Figure 10.1) and used throughout each of the earlier case studies.

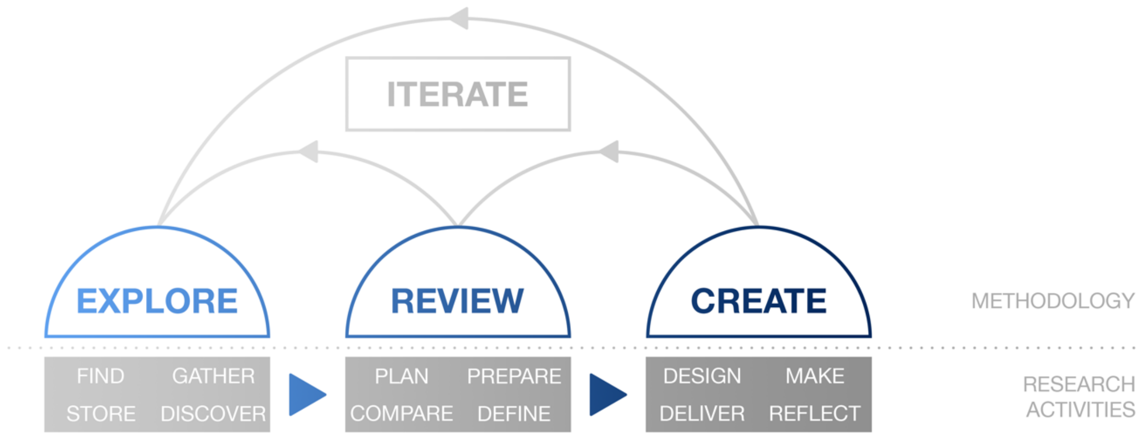

*Figure 10.1: Extract from the author's **Explore Review Create** methodology*

10.1 Explore

In developing an appropriate data grading scale the author first *explored* existing measurement and grading systems, taking the form of a series of online searches. Many results were not included because they were deemed only to be a means of labelling data and did not provide a structured classification scheme using defined criteria. For example, *IMDb*[72] ratings were not included as these offer numerical scores from 1 to 10, where films and TV shows are scored based on subjective user ratings. In contrast, the *Beaufort wind force scale* was included as it allocates a Beaufort number (from 1 to 12), with each step providing a description (such as 'calm' or 'violent') alongside numerical bands for both wind speed and wave height.

A variety of fields and disciplines were included to offer a broader look at how different types of data are measured and classified. This ranged from sexuality (the *Kinsey Scale*) to sound levels (*decibels*) to spicy heat (the *Scoville Scale*). Many of

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[72] IMDb, or Internet Movie Database, is an online database for movies, television and video games, offering information on cast and crew, trivia, and user ratings.

these grading systems were found to be very common, such as the Richter scale or variants of temperature (Celsius, Fahrenheit and Kelvin). However, many others were found to be unusual. The Hamilton-Norwood Scale uses seven progressing images to define male pattern baldness. The theoretical Kardashev Scale provides a means of classifying a civilisation's level based on their technological advancement, using three categories with specific criteria.

Though not exhaustive, a list of these grading systems is provided in Appendix 14.4, alongside a brief description of their purpose and how each system measures data.

10.2 Review

After finding and gathering information on a wide variety of data grading systems, the author undertook a *review* of differences and similarities across these. This was an important step as it would later inform the creation of a grading scale for subsea survey data.

One of the key observations was that each scale had specified criteria, many of which were generally organised into ordered bands. Two examples of this are the Fujita scale (for rating tornado intensity, based on the damage inflicted) and the Saffir-Simpson scale (for classifying Western Hemisphere tropical cyclones). Each of these systems allocates their own classification primarily using recorded wind speed. As a result, this provides a very clear set of successive categories based upon real-world measurements. However, some grading systems were far more binary in their approach – despite having a clear set of criteria and standards, beaches either *are* Blue Flag or *are not*.

Many grading systems used a progressive numerical system (e.g. 1 to 5, or 0 to 9); of these, the higher numbers were typically used to represent the 'best', highest or most extreme results. Using the previous weather-based examples, a higher number from either the Fujita or Saffir-Simpson scale would represent faster and more violent wind speeds. However, though this approach of moving upwards through numbers is relatively common, it is not always the case and there can be advantages in reversing this approach. An example of this is the Energy Performance Certificate scheme – where numbers have been replaced by letters (A through G) and the best energy performance is awarded an A-rating. The Bortle Scale[73] also takes an alternative approach, where values are graded from 1 to 9 and a value of 1 is considered the best result. After reviewing a range of data grading scales, the author found that it does not seem to matter the direction in which results are placed, as long as these are well-structured and made clear to those using such a scale.

Figure 10.2: Wong-Baker FACES® is an example of a grading system with added visuals

An important element that should be considered is the use of visuals as part of a grading system. In some instances, these visuals are used as the primary means of grading information; an example of this is the *Wong-Baker FACES® Pain Rating Scale* (Figure 10.2), developed to assist in identifying patient pain levels. The added use of visuals can aid patients who cannot count or may have impaired brain function.

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[73] A nine-level numerical scale used to measure the brightness of the night sky at a particular location, with relevance to astronomical observation and the impact of light pollution.

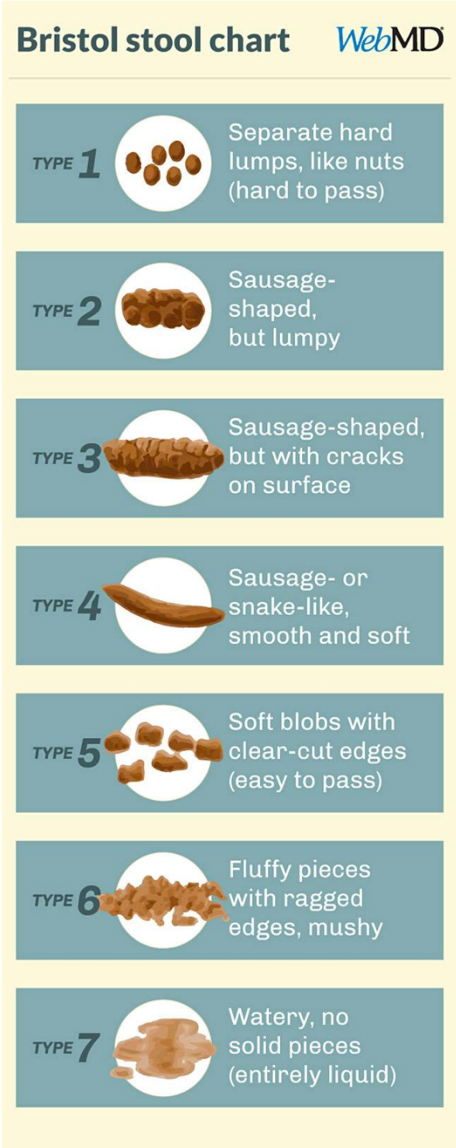

Figure 10.3: Bristol Stool Scale with added visuals (WebMD, 2017)

Other data grading systems offer visuals as a supplementary feature, as a means of better explaining their data categorisation method. The *Bristol Stool Scale* is used as a diagnostic medical tool to aid in classifying human faeces into one of seven types. Each type has a written definition, but is usually accompanied with a drawn cartoon-like image to assist users (shown in Figure 10.3). Without the visual addition of the types, categorising these would become dependent on the written description resulting in less objective classification.

Finally, one means of incorporating visuals into a grading system is where the recognition of an image becomes more important than the details of the grading system itself. An example of this is the *British Standards Institution* and the use of their *Kitemark™* logo (shown in Figure 10.4). This status is awarded to products and services which have successfully passed a series of rigorous tests, resulting in a recognisable logo synonymous with quality. Consequently, the specific details of any testing are often less known to consumers, who instead rely on the logo as an indication that some amount of quality testing has been undertaken.

Figure 10.4: Kitemark™ is a trademarked logo owned by BSI Group

10.3 Create

Building on the *explore* and *review* stages, the author undertook the *creation* of a grading scale which could be applied to subsea survey data for visualisation purposes. A first draft of this framework is shown in Figure 10.5, titled the **Gauld Star Scale**.

Using this grading scale, datasets can be assessed against a set of criteria. These criteria reflect the highest data quality standards which can be achieved when using multibeam survey data, and the resulting number of stars indicates the quality of a dataset in aiming towards this standard. It is important to note that at this early stage the Gauld Star Scale was considered a draft framework, and therefore the specific criteria had not yet been fully established. Instead, generic descriptions were included – for example, *excellent* or *5-star* data should be considered as data which meets **all** of the essential and desirable criteria.

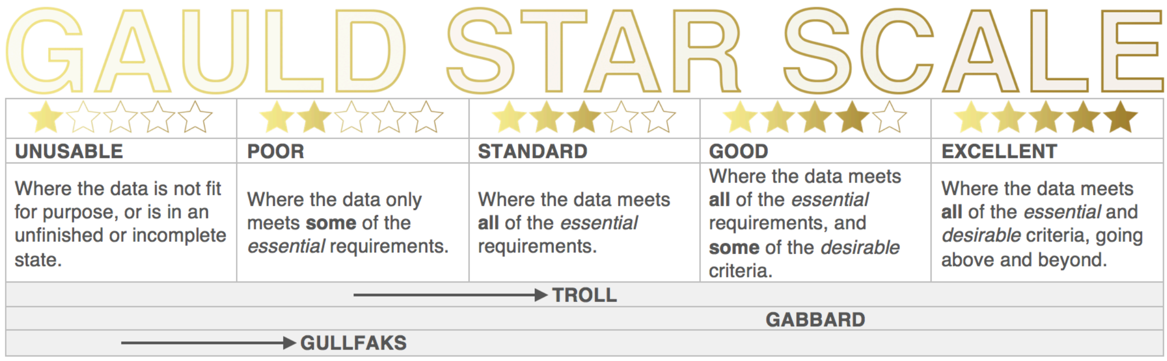

Figure 10.5: ***Gauld Star Scale*** *(first draft of a subsea survey data grading scale, with each of the author's case studies placed as part of this)*

In creating the Gauld Star Scale a variety of factors were considered. Decision-making was based upon the findings gathered throughout the *review* stage of the process. For example, the scale was built using a numerical system (1-5), and a matching number of gold stars were added to each numerical value. Five stars represented the best result (i.e. the best quality of graded data), and star icons were added for visual familiarity and added clarity when comparing graded datasets to one another. In addition to the five-star system, each numerical value had a single-word descriptor (such as *unusable* or *excellent*) assigned to it, and included a further description of how these would relate to the data quality criteria (such as *poor* or *2-star* data being data that only met some of the essential requirements).

As an initial test, each of the author's three case studies (Troll, Gabbard, and Gullfaks) were assessed using this early version of the Gauld Star Scale grading framework. The original Troll dataset was considered as *2-star*, though would be upgraded to *3-star* after including the additional processing undertaken by the 3DVisLab (this change is represented by an arrow in Figure 10.5). With greater involvement from ADUS DeepOcean in acquiring the high-resolution Gabbard data, the resulting datasets were of a higher quality and were scored as *4-star,* providing greater visualisation options. Finally, the Gullfaks dataset was rated as *1-star* prior to the additional post-processing undertaken by the author, as it was considered unusable. This was updated to *2-stars* afterwards, as some useful results were generated. However, it would be extremely unlikely that any further improvements could be made to the Gullfaks dataset – the preferred solution, from a data quality perspective, would be to re-acquire the data using a more considered and robust approach.[74]

It was during these test assessments of case study data that the author realised that without more specific criteria the framework proved to be too vague and resulted in an entirely subjective grading of datasets. Although the framework could be re-applied to different fields or data types by prioritising appropriate criteria, it did not offer a consistent solution across subsea survey data, beyond all datasets being comparatively graded by the same person. As a result, the author chose to improve the framework and address this flaw.

10.4 Iterate

As part of updating the original grading framework a more appropriate name was first chosen, with the second version being called the Dundee Data Grading Scale (or Dundee Scale). A 5-star grading system was maintained – this was largely due to it being both familiar and easily recognisable. Though only a minor difference in format, it was decided that the ability to compare *3-star* data to *5-star* data is much more familiar and intuitive than the alternatives, such as comparing whether *Grade 3* data is better or worse than *Grade 5* data.

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[74] This was also the view of the industry partner, ADUS DeepOcean, who had a preference for offering a complete process – where they would acquire data using specialist survey techniques, followed by undertaking all processing and visualisation in collaboration with the 3DVisLab as required.

An improved grading method was created by adapting the scale to a flowchart-styled set of questions. This created a more specific grading method, which could also be replicated across different datasets uniformly and independently of who was responsible for the data grading. Five critical elements were selected, based on the author's experience with, and reflection on, working closely with subsea survey data. These elements were arranged in order of importance, starting with the most important. Each was presented in the form of a question and was improved and refined multiple times in an attempt to improve clarity but also to remove too much focus on only multibeam survey data. This could allow the grading model to be more-easily adapted for use in other industries or with other data types. The resulting five questions are presented as follows:

- Is the dataset in a recognised format that can be opened successfully?
- Can the dataset be considered complete (i.e. with no missing files or scan data)?
- Does the dataset include all supplementary post-processing information (e.g. location data or motion corrections)?
- Is the dataset of an appropriately high resolution (where objects are clearly visible)?
- Can the dataset be considered accurate and noise-free (where objects are clearly defined)?

Though traces of grader bias and subjectivity have been removed wherever possible, this still remains to a small extent. Due to the nature of subsea survey data in particular, where there are a wide range of views on defining topics such as *high resolution* alongside a wide variety of data uses, the data grader will still be responsible for deciding what is appropriate. For example, a different resolution of data is necessary in accurately finding and measuring objects smaller than one metre when compared to locating larger objects such as shipwrecks.

DUNDEE DATA GRADING SCALE

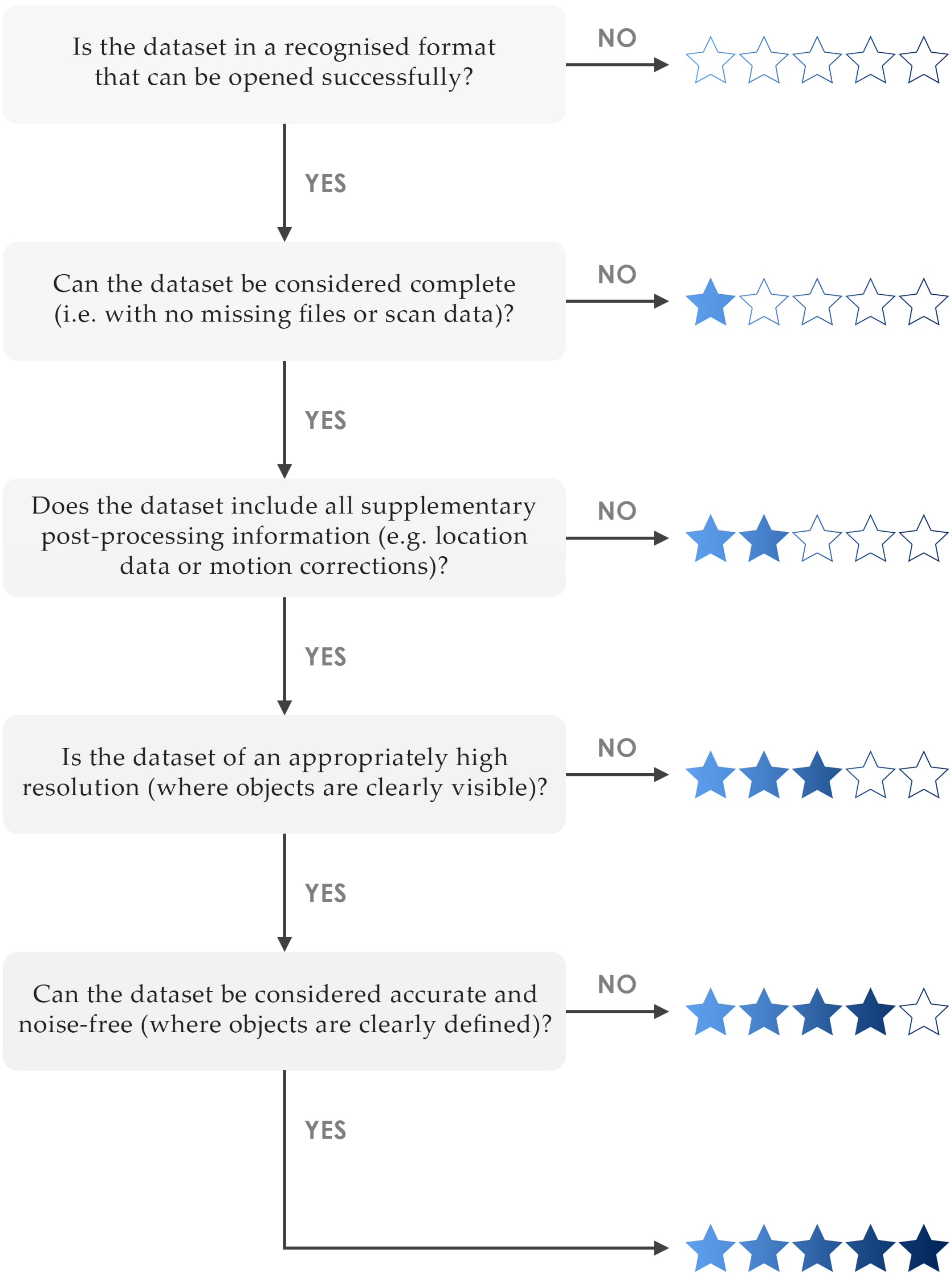

Figure 10.6: Dundee Data Grading Scale

The improved Dundee Data Grading Scale is proposed in Figure 10.6, and is applied by starting at the top and answering the sequence of questions about the dataset being graded. A score, in the form of a number of stars, is generated which can be used to compare the quality of each graded dataset against another. As the focus has been on multibeam data throughout the research activities (section 4.4), this version of the grading system is intended to be used by visualisation and survey practitioners working with multibeam sonar data, though it could be later adapted for other data types.

The Dundee Scale also gives an indication as to what visualisation results are possible. For example, a *0-star* rating means that the data was entirely un-openable and therefore no visualisation results will be possible. In contrast, a *5-star* score means that the data could likely be used with the intention of creating a digital surface model as part of a 3D printing process, with minimal problems faced in doing so.

	Troll	**Gabbard**	**Gullfaks**
Is the dataset in a recognised format that can be opened?	Y	Y	Y
Can the dataset be considered complete?	Y	Y	Y
Does the dataset include all supplementary post-processing information?	Y	Y	**N**
Is the dataset of an appropriately high resolution?	**N**	Y	
Can the dataset be considered accurate and noise-free?		**N**	
	★★★☆☆	★★★★☆	★★☆☆☆

Table 10.1: Results of using the Dundee Scale to grade case study datasets

As with the draft Gauld Star Scale, the proposed Dundee Scale was tested using each of the author's three case studies. Table 10.1 shows the results of the test grading, and includes the final star rating of each dataset. Of particular note is that the grading results are identical to those generated using the original Gauld Star Scale, though are achieved through the use of criteria which have clearer definitions.

10.5 Evaluate

Further evaluation of the Dundee Scale was undertaken using online interviews completed by industry experts. Online interviews were selected as the most appropriate method under the circumstances – due to the nature of the offshore industry, many professionals regularly undertake international fieldwork and arranging face-to-face interviews was not possible. In addition, these experts often spend large amounts of time with unreliable or no internet access and so video-conferencing was also not an option. Instead, the participants were able to download the interview questions in Microsoft Word format, complete these offline in their own time, and return them when regular internet access was resumed.

Participants were provided with an information sheet and consent form alongside the interview questions, and ethical approval was granted prior to the study beginning (appendix 14.3 contains the full ethics application). Experts were identified during the author's commercial practice and recruited based on their industry experience. The completed and returned interview documents are provided in full in appendix 14.4, and the participants evaluation of the Dundee Scale is discussed in this section.[75]

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[75] *Section B* of the expert interviews is not included in this discussion as it does not relate to the evaluation of the Dundee Data Grading Scale.

10.5.1 Section A

The aim of the first questions was to establish the relevant expertise of the participants, and why their views and opinions accurately reflect those of current industry practitioners. Using the responses to question A1, Table 10.2 shows a breakdown of the participants areas of experience, where all of the participating experts have had direct experience of working with both 3D visualisation and subsea survey data.

	Computer graphics and animation	Making	3D visualisation	Subsea survey data
Expert A			•	•
Expert B			•	•
Expert C		•	•	•

Table 10.2: Collated responses to expert interviews question A1 (participant experience)

Further information on each of the participants previous knowledge was also provided. *Expert A* is a researcher and software developer with more than 10 years of experience in the marine salvage industry, with particular experience in developing custom 3D visualisation software and visualising historic shipwrecks. *Expert B* has more than 25 years of experience in maritime related sectors (including salvage and wreck removal, offshore renewables, oil and gas, and defence), with extensive experience in marine forensics and maritime digitalisation including work on high-profile cases such as the Deepwater Horizon oil rig and Costa Concordia wreck. *Expert C* is a hydrographic surveyor and founder/director of a leading subsea 3D survey company, with more than 15 years in the survey industry (Ultrabeam Limited, no date). Experts were invited from a range of areas, each bringing a unique set of experiences and ideas. Together, these would offer a more varied range of evaluations, offering additional improvements and suggestions which the author alone may not have identified.

10.5.2 Section C

The questions in this section of the expert interviews were used to help establish the qualities of good and bad data, and the main challenges which are faced when working with subsea survey data. These topics were particularly important because it would help identify if the Dundee Scale is addressing appropriate criteria, or if better options could be selected.

Prior to reviewing the interview responses, the author's background (chapter 4), contextual review (chapter 5) and reflection on commercial practice had informed the creation of the Dundee Scale. There were four key issues when working with multibeam sonar data which had been identified: poor sonar coverage, missing information (such as location data), low resolution/density data, high levels of noise/inaccuracy. These issues form the basis of the criteria defining the Dundee Scale.

In describing the features of good and bad quality subsea survey data, the industry experts identified and confirmed the relevance of each of these issues, though with minor differences in terminology (e.g. preferring density to resolution). In addition, a number of additional important points were suggested. *Expert A* noted that coverage should also include oblique capture (i.e. using angled sonar in addition to top-down, as shown earlier in Figure 8.9). *Expert B* also added a note alongside their inclusion of high accuracy, stating that this should be "where required", suggesting that the minimum level of accuracy required should be considered as part of each project's budget and time management. *Expert C* also emphasised the importance of survey lines aligning correctly (the Gullfaks project is a key example of survey lines that do not align), and stated that one of the biggest challenges faced was the "precise control of [an] acquisition platform" – something which had not been considered by the author, or mentioned by the other experts. As *Expert C* has significant experience of the practical and technical aspects of surveying, this is an important contribution and further develops the idea of maintaining an overall awareness of what each stage of the surveying process requires.

Based on all of the expert responses, it is suggested that the best quality data is data which is accurate, noise-free, and correctly aligned. Addressing each of these early in the surveying process (as early as ensuring the acquisition vessel sails clean lines, for example) helps avoid significant data problems later during processing or visualisation.

10.5.3 Section D

This set of questions asked participants to provide views on three main topics: identifying similar grading systems they may have encountered, evaluating how successful the Dundee Scale is, and providing suggestions on how to develop and improve the Dundee Scale further.

In response to questions D1 and D2, both *Expert A* and *Expert C* stated that they had not encountered any guidance on best practice, including the use of metadata or paradata, when working with subsea survey data. They also stated that they were not aware of any similar activities or standards currently used to grade or evaluate subsea survey data. This aligns with the lack of relevant grading systems identified throughout the contextual review. *Expert B* suggested that there may be guidance available in the form of "in-house practices" or the use of metrics reporting margins of error. When asked to compare other existing methods of grading subsea survey data to the Dundee Scale (question D3), no responses were provided by any of the industry experts, implying that although companies may have their own internal procedures, no known grading systems were identified for comparison.

In rating the overall success of the Dundee Scale (question D4), the scale received positive feedback, though there was some room for improvement and suggestions were provided on how to achieve this. *Expert A* described it as "a sensible and useful approach to data grading", scoring it 5 out of 5. *Expert C* rated the Dundee Scale as 4 out of 5, describing it as a "good way of instantly comparing data sets of differing quality". *Expert B* scored this 3 out of 5 believing the scale to be "too linear" and "limited to datasets derived from [multibeam sonar]". This is an important observation, as participants were not advised on which type of datasets the scale was applicable to. As defined in section 4.4, the focus and scope of this research has been in addressing multibeam sonar and its visualisation challenges and so the Dundee Scale (in its proposed draft form) is designed to be used with multibeam sonar data. Though this can be seen as a limitation in its current form, it does show that the industry experts were able to identify the intended usage of the Dundee Scale.

Expert B raised an excellent point in asking how "point cloud datasets derived from photogrammetry would fit into this grading process?". Though not the focus of this research, the author fully expects that photogrammetric survey data would experience different data challenges resulting in a different set of grading criteria. This is a key point which can be used to inform and improve future versions of the Dundee Scale, and could be addressed by having a new initial question to select a data source (e.g. multibeam, laser or photogrammetric), followed by a set of criteria questions appropriate to the data type selected.

Participants were also asked to identify the advantages and disadvantages of using the Dundee Data Grading Scale (question D5). Both *Expert A* and *Expert B* described the grading scale as "useful". *Expert* C stated that a 5-point data grading scale may be too basic, suggesting that such a scale "may miss details". This is a fair observation from someone with a high level of technical understanding, though it should be noted that the intention of the Dundee Scale is to allow for grading and comparing datasets quickly and simply, and without requiring significant expert knowledge to use. *Expert A* believes the grading scale could "inform the cost of producing a data visualisation", though advises that it should not result in excluding low-scoring data which can be recovered through additional processing. This echoes the author's experience when using the Gullfaks datasets, which required a significant amount of investment and additional processing though did eventually return useful results. *Expert B* was more critical of the grading scale, suggesting that additional focus should be on the reason for the acquisition of the survey data. For example, metrology data would have a "far higher standard of accuracy required" than general bathymetric survey data. Though the Dundee Scale does not make such a distinction, this issue has been previously considered by the author and the grading criteria are deliberately flexible – the scale asks "can the dataset be considered accurate and noise-free" with no predetermined metrics, allowing for a different accuracy requirement on a per-project basis. Alternatively, this could also be addressed by first selecting the survey purpose or quality requirements and then tailoring the subsequent grading questions, as could be done for different data acquisition methods.

Finally, the experts were asked to comment on the specific grading criteria used by the Dundee Scale (question D6) and how they would improve the scale (question D7). *Expert A* stated that they "would not alter the grading criteria", and that in its current form, for salvage and Inspection, Maintenance and Repair (IMR) purposes, "the scheme as proposed would serve these applications well". Mirroring earlier comments from *Expert B*, it was also suggested that the grading scale could be expanded to accommodate different acquisition methods, in particular photogrammetry. *Expert C* believes that the Dundee Scale would be improved by including example images of data alongside each of the five questions. This is an interesting comment as it echoes the authors earlier findings where some grading systems benefitted from the inclusion of images for adding clarity and improving objectivity (section 10.2). In this instance, including multibeam data images could prove useful in grading multibeam data consistently next to the provided examples, though this is something that would need be explored and compared further before any conclusions could be drawn. However, it is also likely that including pre-selected data images would immediately limit the application of the scale to the type of data being shown alongside the questions – something which the author has worked to avoid during the creation of the Dundee Data Grading Scale, and which the other industry experts were critical of.

10.6 Summary

This chapter detailed the creation and improvement of a data grading scale which can be used for multibeam survey data, or adapted to other areas of data visualisation as required. Evaluation of the grading scale by industry experts offered insight into how effective the scale is and how it can be improved, leading to future research and development.

The first sections of this chapter involved exploring a variety of existing data grading systems, where common elements could be identified. This process contributed to the creation of the draft Gauld Star Scale, which was developed and tested using each of the three case studies as example datasets. These test results were used to inform and iterate, resulting in an updated data grading scale – the Dundee Data Grading Scale – which allows datasets to be graded against one another with increased objectivity, and can be used to assess multibeam survey data for visualisation purposes.

Finally, it is important to note that although some testing was undertaken, the Dundee Data Grading Scale still represents a first proposal towards a fully-developed grading system. Future work could involve further testing of the grading scale in the form of applying this to a wider variety of datasets for further evaluation. This could also be expanded to include validation across different disciplines which also use point cloud data, such as medical or scientific visualisation.

11 Summary and Conclusion

This chapter reviews the contribution of each research chapter to the overall research and its outcomes. The research themes and their relevance to both this and future work are explored and the research questions are addressed.

11.1 Research themes

Throughout the contextual review and each of the case studies, a series of research themes emerged and were identified as key areas of interest. Figure 3.1 shows the relevance of each case study to these five themes. The following sub-sections summarise the completed research activities and their role in developing and addressing each theme.

11.1.1 Pipeline

In understanding and improving the technical pipeline being used with subsea survey data, all three case studies played a critical role. Each of these research chapters contributed differently to developing the three distinct stages of the data lifecycle – acquisition, processing and visualisation (as shown in Figure 11.1).

The Troll case study played a minimal role in understanding the broader pipeline and instead focused on visualisation. Gabbard had a clear focus on acquiring and processing data, and finally, Gullfaks provided additional overlap by further exploring the processing and visualisation of a problematic dataset. The fourth research chapter, which involved creating the Dundee Scale, did not directly contribute to the visualisation pipeline. Instead, the contribution of this chapter was in evaluating and grading the data which would be used throughout these other processes.

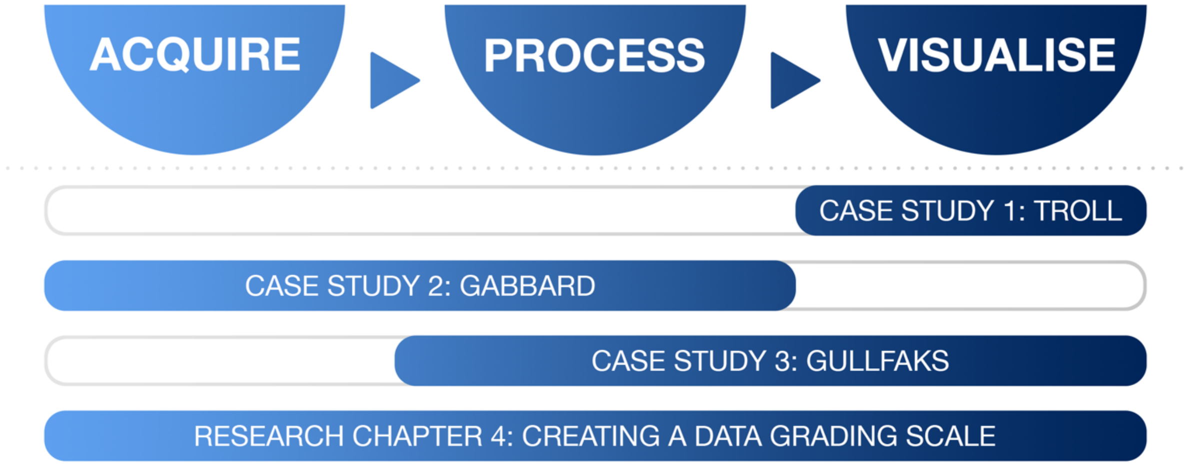

*Figure 11.1: Extract from the **Explore Review Create** framework showing primary focus of each case study*

It is important to note here that the original goal of the author was to explore the *visualisation* of subsea survey data, which directed the focus and research undertaken as part of the Troll case study. It was quickly realised that a better understanding of the entire pipeline (i.e. including acquisition and processing) would produce the strongest results and so Gabbard and Gullfaks covered all of these topics, eventually returning to a more informed view of visualisation.

The Troll case study created an opportunity to explore current visualisation techniques and investigate the application of 3D printing as a visualisation method. This case study allowed the author to develop a clearer understanding of the requirements in 3D printing subsea survey data, and how to overcome any potential issues in doing so. This resulted in successfully creating 3D printed physical models from multibeam sonar data, forming a contribution to subsea visualisation practice and knowledge.

With a series of practical workshops (section 7.6) undertaken to evaluate these different visualisation methods, it was shown that adding the option of 3D printing to the visualisation pipeline is of great relevance and opens up new ways of presenting subsea survey data that are not currently being widely practiced in the industry.

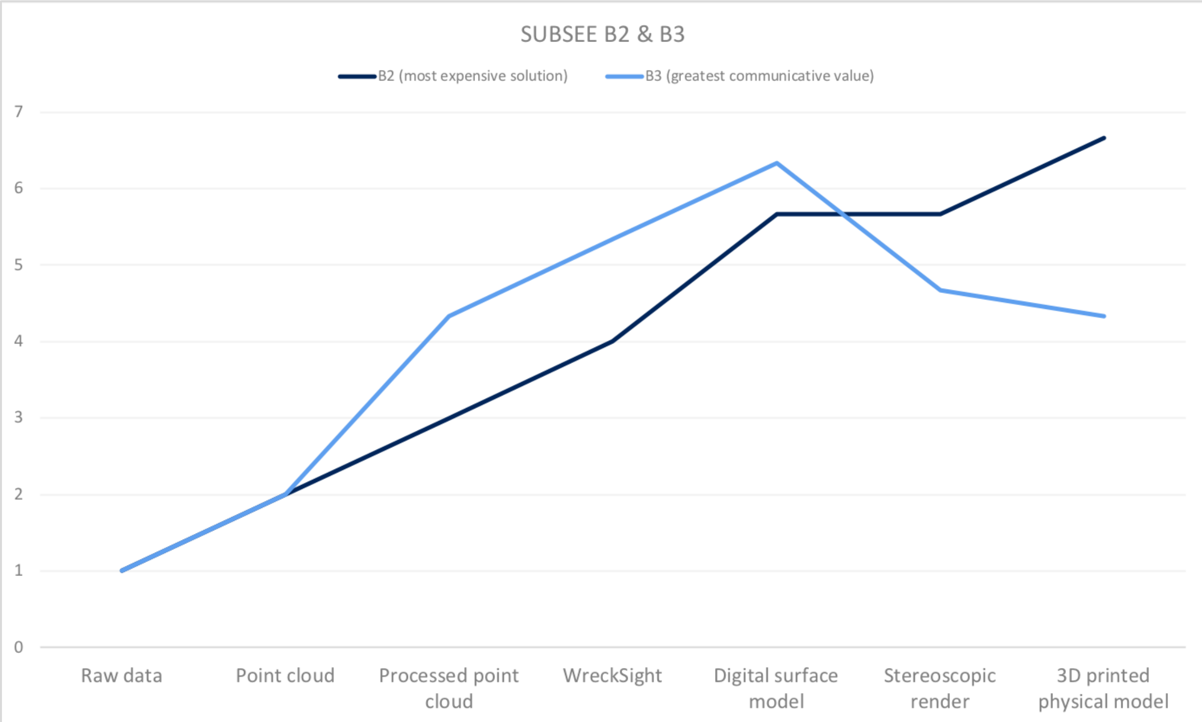

Figure 11.2: Graph comparing the averaged responses to expert interviews questions B2 and B3 (most expensive solution and greatest communicative value)

The expert interviews (questions B2 and B3) explored this topic further offering additional insight into the industry's hesitant adoption of 3D printing. During these online interviews, experts were asked to order seven visualisation methods from 1 to 7, with 7 representing either the most expensive solution (question B2) or the most communicative value (question B3). Figure 11.2 presents these views gathered from the industry experts, highlighting two key findings: processed point clouds, WreckSight and digital surface models offer a higher communicative value than their associated costs; and despite 3D printing offering a good level of communicative value, it is associated with the highest production costs.

Additionally, the industry experts were also asked which of the seven visualisation methods they would like to see used more or less often. Figure 11.3 presents these responses, where the graph presents the total number of responses for the increased or reduced use of each method (where a negative count has been used for methods chosen to be used less often). It is important to note that the interviewed experts did not want to see 3D printing used any less often and so this should still be considered another useful visualisation option available to clients.

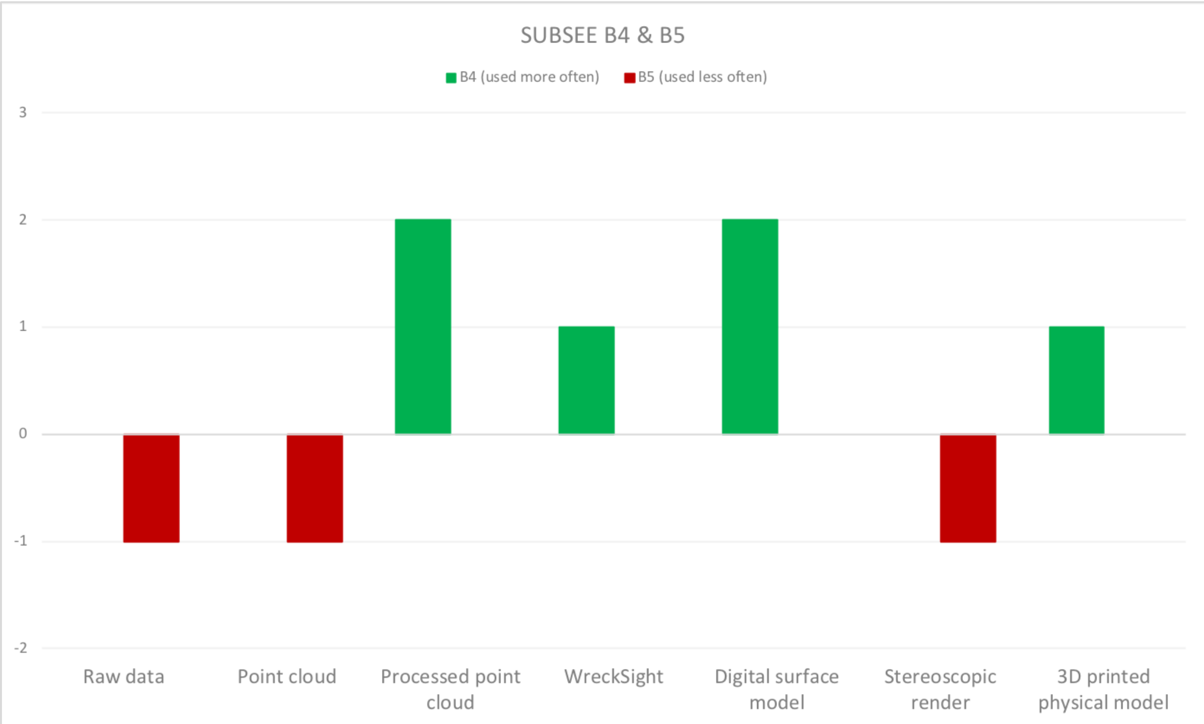

Figure 11.3: Graph comparing the counted responses to expert interviews questions B4 and B5 (using visualisation techniques more or less often)

The Gabbard case study offered a unique insight into a professional team working on a large-scale high-resolution surveying project. Applying the knowledge gained during the data acquisition and processing stages had a significant impact as this highlighted the potential benefits of a data grading system to ensure consistently high-quality visualisation results. The author's Dundee Scale was created in response to this lack of data grading system identified during both the contextual review and commercial practice.

In addition, the Gabbard data processing undertaken by the author provided opportunities to examine each task, to better estimate the typical time to complete, and to identify any areas which could be improved. However, not all of these were implemented – for example, automating the removal of 'zero depth points' across a large number of like-for-like datasets. This raised an interesting set of views which contrasted a need for research and development into new techniques with the application of those which are tried and tested, even if they are more time consuming to complete. Though this research has resulted in the creation of new and essential visualisation tools (appendix 14.2), further research into a consolidated technical pipeline would be beneficial to visualisation practitioners, where the goal should be identifying and creating improvements instead of ruling out ideas because they break away from the traditional approach.

The Gullfaks case study also contributed greatly to the author's improved understanding of the subsea survey data pipeline. Due to the significant challenges faced as part of working with the provided data, Gullfaks' biggest contribution to knowledge was twofold: developing and testing several new approaches to data processing with the most appropriate solutions being successfully implemented as part of a commercial project, and the resulting creation of additional visualisation tools to address common multibeam data problems (appendix 14.2). These techniques and tools contribute to a more complete visualisation toolbox which can be applied to a variety of future projects, including those both in and beyond subsea surveying.[76]

11.1.2 Automation

[76] The *loadWreck* tools created by the author have already been adapted for another member of the 3DVisLab to use with photogrammetric point data, as part of a cultural heritage project.

As part of the research practice, the automation of processing and visualising subsea survey data was investigated, and in some cases, further developed. Some of the simpler or more repetitive tasks were already found to be automated, and in most cases met the requirements of the author throughout each of the case studies. However, there were still some tasks which would benefit from automation – for example, loading point cloud data using Maya was re-visited as part of the Gullfaks case study where updated loading tools (*loadWreck* and its variants) were created and would no longer be dependent on a particular version of software. Additional tools created by the author have been discussed throughout the research, and each of these are presented in appendix 14.2, in full.

In chapter 3, a more conceptual view of automation was also introduced – one which questioned whether a task *should* be automated rather than if it *can* be automated. Continuing to undertake tasks manually would therefore rely on the application of the tacit knowledge of an expert data processor.

The Troll case study included an example of a working process which should not yet be automated – surfacing multibeam point cloud data which includes complex structures or objects. Identified through the author's practice as research, this is largely due to the imprecise nature of multibeam survey data (where data is often low density and experiences high levels of noise) combined with a computers inability to recognise or 'see' a complicated structure. As a result, it is the author's finding that this type of task should continue to be completed manually, and by someone with a suitable amount of first-hand experience with the particular type of data being surfaced. That is, until automatic surfacing techniques become more sophisticated – though that is beyond the scope of this investigation, instead requiring a different skill-set to both evaluate and achieve.

As part of the Gabbard case study, an opportunity to improve the removal of 'zero depth points' was identified. As there were 1,258 data files to process, the automatic removal of these easily identifiable and unnecessary points would be quicker than loading each file individually and removing them manually. Although the necessary development to achieve this was not undertaken as part of the Gabbard case study, a similar process was later undertaken during the Gullfaks practice where points were removed from a dataset if they were positioned outside of a defined distanced from zero. Using the custom scripting tools created during this research as a basis, and adapting them to remove points that had a vertical depth value of less than ten centimetres (for example) would yield useful results in completing a project with similar data to the Gabbard files. The practical development later undertaken confirmed the author's belief that creating such a tool would be both possible and beneficial, and although it did not benefit the Gabbard project files, it could be later re-used across new datasets and projects as required.

During the Gullfaks case study, it was identified relatively early on that the provided data files did not contain any positioning information. As a result, recreating the completed structure from each of the scan segments automatically was no longer possible, and this resulted in a significant amount of time invested to create an alternative and workable solution. This is an example of where being able to automate a task successfully would have dramatically reduced processing time, therefore providing a stronger commercial solution at a reduced cost. It was, however, dependant on those originally undertaking the data acquisition knowing the importance of positioning information at a later point in the visualisation process. This further reinforces the notion that a firm and shared understanding of the entire working process (beyond that of each individual's own role) can prove to be of great benefit overall, mirroring the author's approach throughout the case studies where there was a focus on visualisation as part of a complete data lifecycle.

11.1.3 Digital vs physical

Comparing digital and physical representations of subsea survey data formed an unexpected though important part of this research. Just as there was a clear focus on improving the ways in which we acquire and process data to improve the visualisation outcomes, there should also be a clear goal of broadening and improving the techniques used to present data.

The Troll case study formed the primary basis for exploring the differences between digital and physical visualisations, using different presentations of the same dataset. As detailed in sections 7.5.4 and 7.5.5, this was a somewhat challenging process and the author encountered a variety of new problems. As shown throughout the contextual review, many of these problems were due to working with multibeam sonar data specifically. With these issues now resolved and documented, new knowledge can be shared with the 3DVisLab and ADUS DeepOcean to enable a smoother process of preparing and printing 3D models using subsea survey data. Further evaluation using a series of workshops (section 7.6) compared the impact of different visualisation methods. Following some exploratory reflection and analysis of the user results, it became clear that while on-screen visualisation methods made the data understandable, it was the use of surface models, stereoscopy and 3D printing that moved this forward to become both interesting and exciting.

	Raw data	Point cloud	Processed point cloud	WreckSight	Digital surface model	Stereoscopic render	3D printed physical model
Expert A	•	•	•	•			
Expert B			•		•		
Expert C	•		•		•		

Table 11.1: Collated responses to expert interviews question B1 (which visualisation techniques are regularly provided as client deliverables)

The expert interviews explored this further with question B1, asking industry experts to identify which visualisation techniques they regularly see provided as client deliverables. Experts marked those which they believe are regularly provided with an 'X' and Table 11.1 shows the collated responses to question B1, revealing that it is stereoscopy and 3D printing which do not see regular industry usage (indicated by none of the industry experts marking these choices). The author suggests that this is due to their communicative value being outweighed by increased production costs (Figure 11.2). However, value can be subjective and a 3D printed physical model may be of more value to a client who recognises that it provides a better solution for their particular needs, despite incurring additional expense.

Working with the Gabbard datasets as part of the commercial project did not offer any further comparison between digital and physical visualisations, instead offering a library of data which was *later* used to contribute towards this research theme. The simplicity of the Gabbard datasets (when compared to the Troll structure) allowed for large areas of relatively flat seabed to be surfaced automatically, quickly providing a digital surface model for 3D printing.

Due to the limited quality of the Gullfaks dataset, 3D printing was simply not possible with the supplied data files. As such, there was no option to compare digital and physical representations as part of this case study.

11.1.4 Value

As the value of visualisation will typically vary across disciplines and type of data being used, it is useful to look towards future research to inform and define the common elements in a structured and recognisable way. This also shares some relevance with the concept of data grading, where there are clear criteria which will provide an indication as to how good, or useful, the data really is.

The author first used the workshops undertaken as part of the Troll case study in an attempt to understand and begin to measure one type of value – communicative value. From the workshop results, it was clear where one visualisation technique had a higher communicative value than another (Figure 7.22). For example, raw data had virtually no communicative value to the user groups and was deemed almost entirely incomprehensible. That is not to say that raw data has *no* value, as processing raw data instead of loading point cloud data proved to be of greater *time* value during the Gullfaks case study where significant time savings were achieved – a more literal interpretation of the idea of value, where cost-savings have a commercial significance. Further evaluation of communicative value was completed using the author's expert interviews (Figure 5.4 and Figure 11.2), where digital surface models were identified by industry experts as offering the greatest communicative value, closely followed by the use of 3D printed physical models or WreckSight.

Throughout the Gullfaks case study, the idea of value played a critical role. Since the provided data had not previously yielded any useful results, ADUS DeepOcean were given an opportunity to attempt to generate *value* for the client, in the form of measurable datasets which could be compared. As a result of the collaboration with the author and the 3DVisLab, measurable datasets with improved accuracy and clarity were generated from the problematic files supplied, which were then of use to the client who had previously discounted the acquired data. In addition, the increased knowledge of data processing techniques and expanded visualisation toolbox (appendix 14.2) gained by completing the necessary research and development to achieve this would be of further value to all involved.

Although the Gabbard case study focussed more on the other research themes, it indirectly addressed another concept of value – addressing client needs. In a commercial setting, it is entirely appropriate to offer alternatives to the requested deliverables which may prove to be more suitable, particularly when budget can often be a significant consideration, or where a client may not be fully aware of what a particular dataset can offer. This echoes the importance of understanding which visualisation options are both available and achievable, and that what is valuable to one client may not be to another – it is essential to consider this throughout any project.

11.1.5 Data quality

An awareness of data quality has proven to be invaluable throughout each of the three case studies presented – without good quality data, it becomes significantly more challenging (and sometimes impossible) to achieve the desired visualisation results.

Each of the datasets and case studies allowed the author to compare the offshore industry's approach to survey data acquisition with their approach to visualisation. ADUS DeepOcean previously developed a series of factors which should be considered and addressed during acquisition, offering a heightened awareness of acquisition quality and continue to ensure that data gathering opportunities are maximised fully. Alongside the author's commercial practice and views gathered from industry experts, the contextual review identified no similar systems for evaluating or grading subsea survey datasets against each other for visualisation purposes.

As a significant contribution to the field of subsea surveying, the author proposes a system that could be used to grade data for visualisation purposes, in the form of the Dundee Data Grading Scale (Figure 10.6). The creation of this scale is discussed and evaluated in chapter 10, and includes the selection of grading criteria which address the attributes of good or bad quality subsea survey data (with these definitions informed by the responses gathered from industry experts).

Each of the case studies helped define data quality. However, in better understanding this, the Troll data was considered generally fit for purpose with only minor issues to be resolved. These were completed primarily by the 3DVisLab before being passed to the author, and as such the first case study only contributes to better defining data value conceptually.

One of the key goals of the Gabbard case study was for the author to better understand the entire pipeline – in particular the acquisition and processing stages as they relate and contribute to overall data quality. In contrast to the Troll project and its resulting dataset, ADUS DeepOcean were responsible for all of the Gabbard stages from acquisition to final deliverable, creating an opportunity to contrast the different outcomes. It was clear that with adequate care during the earlier stages of the data lifecycle, the later stages would be more efficient and produce stronger results – reaffirming the concept of *good data in, good data out* through the author's practice and reflection.

In case study three, the work undertaken as part of the Gullfaks project acted as a critical test for *bad data in*. As an example of a poorly acquired dataset, which had been all-but-abandoned, there was very little hope for useful results being generated. Given the opportunity, an ideal solution would have been for ADUS DeepOcean to re-acquire the data, but this was not possible. Alternatively, the processing work undertaken to try and create results from a sub-optimal dataset was challenging and time-consuming, and therefore expensive. Fortunately, the client was willing to pay for the necessary expertise, and through the creation and testing of new processing and visualisation techniques and tools, a measurable and successful outcome was presented to the client. Although these results had a higher margin of error than the client had originally requested, it was considered the best solution available, and if more accurate results were required it was clear that better quality data would need to be gathered. In addition, the time spent on resolving data issues was still of great value as each problem-solving attempt forms a contribution to knowledge, developing the visualisation toolbox available to the author, 3DVisLab and ADUS DeepOcean.

11.2 Research questions

This section will address each of the research questions and how they have been answered by the research activities. These are presented in the following sections, starting with the four sub-questions and concluding with research question zero. The development of the research activities and their outcomes are informed by the research background, contextual review, and creative and commercial practice. Evaluation has been undertaken using a series of workshops, expert interviews, and through the author's own commercial experience and reflection on practice.

11.2.1 RQ1: How effective are current visualisation methods in communicating subsea survey data accurately and clearly?

Evaluated using the Troll workshops and online expert interviews, a series of visualisation methods were directly compared and current methods were shown to have good communicative value, particularly in making raw data clearer and initially more understandable. However, they were also found lacking in interest or excitement when compared to newer visualisation techniques such as stereoscopy or 3D printing, with these being the preferred visualisation methods. In contrast, the expert interviews showed the use of digital surface models to be a better option, offering the greatest communicative value without being outweighed by cost. It should be noted that this cost is already higher than other methods regularly used in industry (largely due to manual surface modeling), and so when asked which visualisation techniques should be used more often, processed point clouds received the greatest level of support.

Though it resulted in no clear rationale for *replacing* current visualisation techniques with stereoscopy or 3D printing, these were included in the evaluation as they can still present three-dimensional data in three-dimensions, and offer an alternative to traditional visualisation techniques. With 3D printing, a physical object is being used to represent the original physical object – offering a 'truer' version of the data being shown. A printed model can also offer improved accessibility, requiring no knowledge of specialist software packages to 'read' and understand. It is important to remember that data is not any less accurate or understandable whether it is viewed on- or off-screen – the data remains the same and the challenge is in choosing the most appropriate presentation method which offers the clearest version of the data, something which largely remains driven by client expectations and requirements.

The author's reflection on the practice-led research completed as part of the Gullfaks case study showed that by creating new visualisation tools and adapting and improving current processing techniques, new meaning can be extracted from challenging or problematic datasets which would otherwise not have been possible. Although the author's expectation was that the inclusion of methods such as 3D printing would offer stronger visualisation results, this is greatly dependent on the quality of multibeam sonar data being gathered, and it is clear that there are still benefits to be gained from developing currently used processing and visualisation methods further. In doing so, new ways to communicate data clearly and as accurately as possible can be achieved, offering improvements to familiar visualisation techniques in place of pushing those which have not yet been readily adopted by the offshore industry and require additional investments in both time and cost.

11.2.2 RQ2: What is the relationship between automation and 3D visualisation of subsea survey data?

The relationship between visualisation and automation remains a complicated yet interesting one. Throughout all three case study chapters, there are examples of tasks which are automated and examples of those which are not. In the case of automating surface modeling of subsea survey data, there is no clear answer – simple datasets (like the Gabbard seabed data) *can* be automatically surfaced, but more complex point clouds (like the Troll structure) cannot. Ultimately, this is dependent on the quality of the resulting survey data, where multibeam sonar data suffers from a number of recurring quality issues. As such, it is clear that there is no 'one size fits all' approach to surfacing subsea survey data, and as with many elements of visualisation, a bespoke approach to each project is taken – one which requires experts and the application of tacit knowledge.

However, there are some tasks which could benefit greatly from increased automation – such as removing 'zero depth points' from 1,258 data files as part of the Gabbard project, or aligning individual scan segments as part of the Gullfaks practice. Despite it being possible to remove the manual element of such tasks, this was not always applied. In the case of the Gullfaks case study, automating time-consuming tasks was not always possible due to the quality of the provided data. In contrast, automation *was* possible during the Gabbard processing but a decision was made to focus on completing tasks manually instead of investing further research and development time.

Prior to undertaking these case studies, the author's approach was to consider whether a task *can* be automated and how this might be achieved. However, due to the varying range in the quality of subsea survey data, it is more appropriate to consider whether a task *should* be automated, often on a project-by-project basis. That is not to say that automation should be avoided, but should instead be considered as another option in the visualisation toolbox, rather than a given part of the process which must be continually developed and achieved regardless.

11.2.3 RQ3: What are the effects on the understanding of subsea survey data in the transitioning between digital and physical 3D representations?

Using the evaluation completed during the Troll workshops and expert interviews, it is clear that there was no change in the basic understanding of subsea survey data in comparing digital and physical 3D representations. That is to say, a 3D printed version of a dataset compared to an equivalent WreckSight package communicates the underlying data in a similar way. This would suggest that there is no need to move beyond current methods for communicative understanding alone.

However, whilst working on commercial projects, the author realised that clients found 3D printed visualisations to be both interesting and useful, such as during board meetings or similar group events and particularly for those who were not familiar with specialist software packages. A physical object could be examined without any software expertise and could be measured easily to aid in decision-making.[77] This opened up opportunities for discussion – offering advantages in an unexpected but entirely practical manner, and beyond that of a digital dataset. With this added knowledge of how physical 3D representations *could* be used in the industry, understanding of the tools and techniques required to create these objects becomes of increased value. As a result, this forms part of the author's contribution to knowledge by adding another visualisation option which could be offered during future projects undertaken by the author, 3DVisLab or ADUS DeepOcean.

It is also important to note that there was not an opportunity to work with data which was both high-quality and of a complex nature (as each dataset addressed only one of these two factors). Further knowledge on transitioning subsea survey data from digital to physical would be improved significantly if access to such datasets could inform the basis of future work

11.2.4 RQ4: What is the measurable value of innovation in 3D visualisation to the subsea surveying industry?

The Troll case study offers a comparative view of different 3D visualisation techniques when applied to subsea survey data, and the results of the Troll workshops and expert interviews show which of those best communicate the underlying data. In addition, the evaluation of visualisation techniques highlights

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[77] With the Troll project, it was expected that the client would use the completed digital surface model to record measurements as this would provide the greatest level of accuracy – it was a surprise to both the author and ADUS DeepOcean to see that the client's decision-makers had preferred the 3D printed physical model for this purpose.

which stages of the data lifecycle offer little or no improvement on the others, and are not typically worth investing additional time and effort into developing. Combined with an improved practical understanding of what each technique involves, this allows for the most appropriate 3D visualisation methods to be selected, while still considering the cost to produce and overall communicative value.

Being able to address each of these factors as part of any commercial project is critical, as it ensures that potential issues can be minimised and work can be completed to an appropriate quality using an established and repeatable workflow. As the contextual review identified no published material which explored the comparative value of different visualisation methods applied to subsea survey data, this is a contribution to new knowledge within the research field.

Additionally, the research and development into alternative ways of processing and visualising data (for example, during the Gullfaks case study) is of great value to the subsea surveying industry, forming another valuable contribution as a result of the author's practice as research. ADUS DeepOcean were offered the Gullfaks project due to their expertise in addressing problematic datasets and delivering bespoke visualisation solutions. Having a diverse and expanding visualisation toolbox creates the best possible scenario for addressing client needs and creating 3D visualisations which are consistently of a high quality – something which could be used to generate additional business. As a result of the work undertaken during the Gabbard project, where 140 wind turbines were surveyed, processed and visualised, ADUS DeepOcean has since completed additional Gabbard surveys on behalf of the same client.

Finally, each of the research activities and further consultation with industry experts confirmed that there was no unified means of grading subsea survey data, which could be used to provide clarity on project deliverables and costs, or compare and evaluate datasets against one another. Although it was suggested that companies may have their own in-house evaluation procedures, it is common for data to be acquired by one company and processed or visualised by another (as experienced during the Troll and Gullfaks projects). A unified grading system would accommodate data handovers and help align subjective views on identifying dataset quality.

For this reason, the most significant innovation and contribution to the subsea surveying industry is an improved understanding of data quality developed alongside the Dundee Data Grading Scale, proposed by the author as a new means of grading and evaluating multibeam sonar survey data. Though this has been developed for multibeam data, evaluation suggested adapting this to include other acquisition methods, and as such, this could form part of future research and improvement.

11.2.5 RQ0: Can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?

By exploring and applying alternative visualisation techniques used in other disciplines, new understanding in processing and visualising subsea survey data was achieved, and resulted in the ability to prepare and print 3D models from multibeam point cloud data. The inclusion of 3D printing offers new ways of viewing subsea survey data, and although this has not yet been widely adopted, 3D printing has shown promise in its application. This enables three-dimensional data to be shown in three-dimensions, returning physical objects to a physical form once more – an improvement in communicating data which was not previously achievable using conventional on-screen visualisation techniques, and did not feature in any of the related literature.

Maintaining an awareness of the complete pipeline – acquisition, processing and visualisation – offers the best possible means of creating high quality 3D visualisations, and combining this with the use of experts throughout each of the stages creates the strongest working environment. Without this considered and all-encompassing approach, subsea survey data can be problematic and create issues which are time consuming to resolve (the Gullfaks dataset is a key example of this).

It is the author's belief that practitioners should hold an essential awareness of the entire data lifecycle, as it can significantly improve the communication and understanding of resulting visualisations. For example, if surveyors do not understand the importance of recording accurate positioning data for processing and visualisation purposes, this can require a significant amount of corrective processing or potentially render a dataset unusable. Though some recovery is possible, this can have a significant impact on the cost and duration of a project.

In addition, there were several practical improvements to the visualisation of subsea survey data as a result of the research activities. The author developed a series of new scripting tools which addressed critical research problems. These tools were used to complete the practical work, and allowed tasks to be completed which were otherwise not possible. The knowledge gained in creating these tools can be used to adapt or create new scripting solutions as and when required, including those which may be needed when using point cloud data beyond subsea surveying.

The author also proposes the Dundee Data Grading Scale which can be used to grade and compare different datasets. This is a significant development as it improves structure and consistency, and provides a clearer understanding of what can be achieved with a particular dataset. It also assists in identifying potential data problems before a significant amount of time (and expense) is committed.

Based on the practice, reflection and outcomes of each of the completed research activities, the author proposes that the communication and understanding of subsea survey data *can* be improved by using 3D visualisation methods. Although it is clear that current visualisation techniques already offer a good level of basic understanding of subsea survey data, there are advantages which are gained by developing these further, and additional benefits identified which could be explored as part of ongoing future research.

11.3 Conclusion

High-resolution subsea survey data offers a new ability to explore difficult or hazardous underwater environments and, using multi-beam sonar, provides three-dimensional bathymetric data for visualisation. The primary focus of this doctoral research was to investigate whether the 3D visualisation of subsea survey data could be improved, and if so, how this might be achieved.

Using the datasets gathered as part of three commercial projects, each case study contributed to the development of the research themes in answering each of the research questions. Using a multi-method approach was appropriate in facilitating the creation of new solutions to each of the identified 3D visualisation problems. These solutions included the application of emerging techniques (such as 3D printing) commonly used in other, more established visualisation disciplines, and the development of new software tools creating a broader and more advanced visualisation toolbox which could be re-applied beyond the scope of this research. Finally, the proposed Dundee Data Grading Scale offers a significant and new contribution to the field of 3D visualisation of subsea survey data, where data is not currently graded or evaluated.

As a result of this practice-led exploration and development, the author proposes that the communication of subsea survey data can be improved by using 3D visualisation, enabling new work to be undertaken with improved understanding of a range of visualisation techniques, and using an expanded visualisation toolbox. Together, the research practice, evaluation and commercial validation of these case studies forms a significant contribution to new knowledge in the 3D visualisation of subsea survey data.

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14 Appendices

14.1 Appendix I: Supplementary datasets

This appendix provides further information on accessing the subsea survey datasets discussed throughout this document, including information on opening and viewing dataset files using CloudCompare. CloudCompare was used by both ADUS DeepOcean and the author, allowing the industry collaborators full access to all of the developing research datasets and outputs without changing their existing processes or workflows.

CloudCompare is freely available under a GNU General Public License and currently runs on Windows, MacOS, and Linux. It is downloadable from the following website: https://www.danielgm.net/cc/

14.1.1 Access to the datasets

Access to the supplementary datasets is restricted – ownership of these datasets remains with the original companies for which the work was undertaken by ADUS DeepOcean. Limited access can be approved in some circumstances. If granted, any access to the datasets will be subject to a non-disclosure agreement with the University of Dundee.

14.1.2 Repository contents

All of the datasets related to this thesis have been collected into a single digital repository. This repository contains the following five root-level folders:

CS1 Troll: Containing raw data files, a processed and combined point cloud, and a complete 3D surface model.

CS2 Gabbard (Data): Consisting of all of the Gabbard data assets processed by the author, one per sub-folder. Due to the storage space required for the entire project, a full set of files is provided for a limited number of assets, marked with [FULL] in their title. Each of these folders contain files from all stages of processing – a set of original QPD files, a Fledermaus project, and a fully-processed and combined BIN file. Otherwise, a fully-processed and combined BIN file is provided. Wind turbine assets also contain TXT files, providing side profiles of the turbine structure and intersection with the seabed.

CS2 Gabbard (Other): Containing PDF maps showing the Gabbard/Galloper site layouts (including asset names), and completed OBJ files used for 3D printing.

CS3 Gullfaks: Showing each stage of the Gullfaks reconstruction process – from raw data, through multiple stages of processing, to completed deliverables. This folder also contains internal background documents which are to be treated as confidential.

Extra: Two smaller projects which were not used as research case studies. *SS Breda* (Data 14.1) includes data processed by the 3DVisLab intended to be used by the author for 3D printing. Although Gabbard data was later selected for this purpose, the folder contains incomplete digital surface models intended to fit together after 3D printing. *SS President Coolidge* (Data 14.2) shows stages of processing leading to presentation as a completed deliverable (undertaken solely by the author).

Data 14.1: Data repository > Extra > SS Breda

Data 14.2: Data repository > Extra > SS President Coolidge

14.1.3 File formats and opening datasets

There are several key data formats found within the digital repository. Each of these are shown below, and most can be opened using CloudCompare. These file formats are indicative of those used throughout each of the practice-led case studies, with data provided simply as a 'list' of XYZ co-ordinates which can be shown as a three-dimensional point cloud (there is no other accompanying information or metadata).

.BIN: Point cloud data containing multiple passes or sections.
.TXT: Point cloud data containing a single line or pass.
.XYZ: Point cloud data containing a single line or pass.
.OBJ (and .MTL): Surface model and related material file.
.QPD: These files require Fledermaus software, and cannot be opened using CloudCompare.
.FMPROJ: These files require Fledermaus software, and cannot be opened using CloudCompare.

Using CloudCompare, datasets can be loaded using **File > Open**. Multiple datasets can be opened simultaneously if required – these will appear in the *DB Tree* pane as different folders containing point cloud sets.

There are also a small number of Autodesk Maya project folders. These follow the default project folder layout and contain a variety of files (such as particle cache files) alongside the openable Maya *scene* files.

14.1.4 Suggestions for viewing datasets

When opening the supplied point cloud data files, it is recommended that *ccViewer* is not used as this offers limited functionality. In particular, *ccViewer* gives no options for viewing individual point clouds within a BIN file, and less control in selecting different colour ramps or shaders to improve visual clarity.

In CloudCompare, the default viewing mode is the orthographic view. Left clicking and dragging will rotate the object(s) being displayed. Scrolling the mouse wheel (or trackpad) will zoom in and out. Right clicking and dragging will pan the object(s) being displayed in the 3D view.

It can often be easier to visually understand basic point cloud data by applying a height-based colour ramp. In the *DB Tree* pane, select the point cloud object (shown with a 'cloud' icon) you want to apply colour to. Then choose **Edit > Colors > Height Ramp** and choose your preferred colour option in the pop-up window – this will then be applied to the selected point cloud.

It can also be beneficial to use either the EDL or SSAO shaders to improve point cloud clarity. These can be applied (or removed) by choosing **Display > Shaders & filters** and picking either *E.D.L.* or *S.S.A.O.* (or *Remove filter*). Point size can also be increased or reduced within the 3D view as appropriate. Using the EDL shader with an increased point size can result in the impression of a more "solid" object being displayed.

14.2 Appendix II: Visualisation tools

This section contains each of the scripts written solely by the author throughout the duration of this research. Each script is written using Maya Embedded Language (MEL) and has been tested on versions of Maya from 2011 onwards.

These scripts were created in response to problems encountered throughout each of the research case studies and form the basis of a 'visualisation toolbox'. They typically relate to the creation of *Maya particles* from subsea survey data, though more specific explanations accompany each script in the following sub-sections.

It is important to note that each of these scripts could be adapted to work with other types of 3D point cloud data – such as medical scan data or laser survey data.

14.2.1 loadWreck

This script can be used to load simple point cloud data – that is, files which contain only X, Y and Z coordinates (typically, one coordinate set per line). It is intended for use with XYZ or TXT files, as these were the most commonly encountered file types when working with subsea survey data.

The script 'reads' the selected point cloud data file line by line and creates a Maya particle object containing all of the points being read. A pop-up window appears upon completion and displays the number of points created and the time taken to complete.

```
// loadWreck Script
// Create Maya particle object from basic point cloud data (coords only)
// NOTE: Only shows/opens XYZ or TXT files
// Created by Dylan Gauld

global proc loadWreck() {
```

```
string $fileFilter = "XYZ files (*.xyz *.txt)";
string $fileName[1] = `fileDialog2 -fileMode 1 -dialogStyle 2 -
  fileFilter $fileFilter`;
$fileId = `fopen $fileName[0] "r"`;
string $nextLine = `fgetline $fileId`;

currentTime 1;

int $i = 0;

if (`objExists pointCloud`) {
      rename pointCloud pointCloudOld;
}

particle -n pointCloud;
setAttr "pointCloudShape.isDynamic" 0;
disconnectAttr time1.outTime pointCloudShape.currentTime;

float $timer = 0;
timer -s;

while ( size ( $nextLine ) > 0 ) {

      $i = ($i + 1);

      string $lineValues[6];
      tokenize ($nextLine, "  ,", $lineValues);
      float $valueX = $lineValues[0];
      float $valueY = $lineValues[1];
      float $valueZ = $lineValues[2];

      emit -o pointCloud
            -pos $valueX $valueY $valueZ;

      $nextLine = `fgetline $fileId`;

}

fclose $fileId;
```

```
	$timer = `timer -e`;

	string $window = `window -title "loadWreck" -mxb 0 -mnb 0`;
	columnLayout -adjustableColumn true;
	text -label ("\nLoaded " + $i + " points in " + $timer + "
	  seconds.\n");
	button -label "Close" -width 200 -height 50 -command ("deleteUI -
	  window " + $window);
	showWindow;
	window -edit -widthHeight 400 100 $window;

}
```

14.2.2 loadWreckRGB1

This script is an adaptation of the *loadWreck* tool, and extends the functionality to load an XYZRGB file – loading a point cloud file that also contains per-point colour attributes.

Maya prefers RGB values in the range 0 to 1 and this script can be used where the data file being loaded contains RGB values in this range.

```
// loadWreckRGB1 Script
// Create Maya particle object from point cloud data (XYZRGB format)
// NOTE: Only shows/opens XYZ or TXT files
// NOTE: Requires RGB values in format 0 to 1
// Created by Dylan Gauld

global proc loadWreckRGB1() {

	string $fileFilter = "XYZ files (*.xyz *.txt)";
	string $fileName[1] = `fileDialog2 -fileMode 1 -dialogStyle 2 -
	  fileFilter $fileFilter`;
	$fileId = `fopen $fileName[0] "r"`;
	string $nextLine = `fgetline $fileId`;

	currentTime 1;
```

```
int $i = 0;

if (`objExists pointCloud`) {
      rename pointCloud pointCloudOld;
}

particle -n pointCloud;
addAttr -ln "rgbPP" -dt vectorArray pointCloudShape;
addAttr -ln "rgbPP0" -dt vectorArray pointCloudShape;
setAttr "pointCloudShape.isDynamic" 0;
disconnectAttr time1.outTime pointCloudShape.currentTime;

float $timer = 0;
timer -s;

while ( size ( $nextLine ) > 0 ) {

      $i = ($i + 1);

      string $lineValues[6];
      tokenize ($nextLine, "  ,", $lineValues);
      float $valueX = $lineValues[0];
      float $valueY = $lineValues[1];
      float $valueZ = $lineValues[2];
      float $valueR = $lineValues[3];
      float $valueG = $lineValues[4];
      float $valueB = $lineValues[5];

      emit -o pointCloud
            -pos $valueX $valueY $valueZ
            -at rgbPP -vv $valueR $valueG $valueB;

      $nextLine = `fgetline $fileId`;

}

fclose $fileId;

$timer = `timer -e`;
```

```
	string $window = `window -title "loadWreckRGB1" -mxb 0 -mnb 0`;
	columnLayout -adjustableColumn true;
	text -label ("\nLoaded " + $i + " points in " + $timer + "
	  seconds.\n");
	button -label "Close" -width 200 -height 50 -command ("deleteUI -
	  window " + $window);
	showWindow;
	window -edit -widthHeight 400 100 $window;

}
```

14.2.3 loadWreckRGB255

This script is a modification of the *loadWreckRGB1* tool, and is used to read an XYZRGB file where the RGB values are supplied in the range 0 to 255. An additional calculation step during particle creation converts each set of RGB values (being read from the data file) to their 0 to 1 equivalents, as preferred by Maya.

```
// loadWreckRGB255 Script
// Create Maya particle object from point cloud data (XYZRGB format)
// NOTE: Only shows/opens XYZ or TXT files
// NOTE: Requires RGB values in format 0 to 255
// Created by Dylan Gauld

global proc loadWreckRGB255() {

	string $fileFilter = "XYZ files (*.xyz *.txt)";
	string $fileName[1] = `fileDialog2 -fileMode 1 -dialogStyle 2 -
	  fileFilter $fileFilter`;
	$fileId = `fopen $fileName[0] "r"`;
	string $nextLine = `fgetline $fileId`;

	currentTime 1;

	int $i = 0;

	if (`objExists pointCloud`) {
		rename pointCloud pointCloudOld;
```

```
}

particle -n pointCloud;
addAttr -ln "rgbPP" -dt vectorArray pointCloudShape;
addAttr -ln "rgbPP0" -dt vectorArray pointCloudShape;
setAttr "pointCloudShape.isDynamic" 0;
disconnectAttr time1.outTime pointCloudShape.currentTime;

float $timer = 0;
timer -s;

while ( size ( $nextLine ) > 0 ) {

      $i = ($i + 1);

      string $lineValues[6];
      tokenize ($nextLine, "  ,", $lineValues);
      float $valueX = $lineValues[0];
      float $valueY = $lineValues[1];
      float $valueZ = $lineValues[2];
      float $valueR = $lineValues[3];
      float $valueG = $lineValues[4];
      float $valueB = $lineValues[5];
      $valueR /= 255;
      $valueG /= 255;
      $valueB /= 255;

      emit -o pointCloud
            -pos $valueX $valueY $valueZ
            -at rgbPP -vv $valueR $valueG $valueB;

      $nextLine = `fgetline $fileId`;

}

fclose $fileId;

$timer = `timer -e`;

string $window = `window -title "loadWreckRGB255" -mxb 0 -mnb 0`;
columnLayout -adjustableColumn true;
```

```
        text -label ("\nLoaded " + $i + " points in " + $timer + "
          seconds.\n");
        button -label "Close" -width 200 -height 50 -command ("deleteUI -
          window " + $window);
        showWindow;
        window -edit -widthHeight 400 100 $window;

}
```

14.2.4 checkWreckZ

This tool can be used to calculate the minimum and maximum Z values for a selected existing particle object in Maya. When using subsea survey data files, Z refers to the height or depth axis. Upon completion of the script, a pop-up window displays the minimum and maximum Z values.

This script was originally intended to form part of a more advanced tool – where the Z range of a particle object would be calculated so that a colour ramp could be automatically applied to the relevant object height range in Maya. It was later decided that this feature was no longer necessary and the remaining script development (applying the colour ramp) was not completed.

```
// checkWreckZ Script
// Calculates min/max Z values (height/depth) for a particle object
// NOTE: Relies on particle object already being selected
// Created by Dylan Gauld

global proc checkWreckZ() {

        string $selected[] = `ls -sl`;

        int $i = 0;
        int $j = `getAttr ($selected[0]+".count")`;
        float $minZ;
        float $maxZ;

```

```
	float $timer = 0;
	timer -s;

	for ($i = 0; $i < $j; $i++) {
		float $posPP[] = `xform -q -t -a -ws
		  ($selected[0]+".pt["+$i+"]")`;
		if ($i == 0) {
			$minZ = $posPP[2];
			$maxZ = $posPP[2];
		} else {
			if ($posPP[2] < $minZ) {
				$minZ = $posPP[2];
			}
			if ($posPP[2] > $maxZ) {
				$maxZ = $posPP[2];
			}
		}
	}

	$timer = `timer -e`;

	string $window = `window -title "checkWreckZ" -mxb 0 -mnb 0`;
	columnLayout -adjustableColumn true;
	text -label ("\nProcess completed in " + $timer + " seconds.");
	text -label ("\nMin Z = "+$minZ);
	text -label ("\n Max Z = "+$maxZ+"\n");
	button -label "Close" -width 200 -height 50 -command ("deleteUI -
	  window " + $window);
	showWindow;
	window -edit -widthHeight 400 150 $window;

}
```

14.2.5 moveWreck

As part of the 3DVisLab's original WreckSight plugins (useable only in Maya 2011) there was a feature titled 'separatePO' which could be used to recreate particle objects with zeroed *translate* values after they had been repositioned in Maya (such as after manually re-positioning scan segments).

The *moveWreck* script addresses this functionality and has been recreated using Maya Embedded Language. As a result, this tool is no longer version-dependant and can be used with versions of Maya after 2011.

Although it only recreates XYZ particle attributes in this current form, it could be extended to include the recreation of RGB values (on a per particle basis) as part of the new particle object.

```
// moveWreck Script
// Recreate existing particle object based on translate offset
// NOTE: Replaces separatePO (used if particle object translate is not 0)
// NOTE: Doesn't recreate RGBPP values
// Created by Dylan Gauld

global proc moveWreck() {

      string $selected[] = `ls -sl`;
      float $offsetX = `getAttr ($selected[0]+".tx")`;
      float $offsetY = `getAttr ($selected[0]+".ty")`;
      float $offsetZ = `getAttr ($selected[0]+".tz")`;
      int $particleCount = `getAttr ($selected[0]+".count")`;

      particle -n ($selected[0]+"OFFSET");
      setAttr ($selected[0]+"OFFSET.isDynamic") 0;
      disconnectAttr time1.outTime
        ($selected[0]+"OFFSETShape.currentTime");

      float $timer = 0;
      timer -s;

      for ($i = 0; $i < $particleCount; ++$i) {

            float $particlePosition[] = `getParticleAttr -at position
              ($selected[0]+".pt["+$i+"]")`;
            float $newPosX = $particlePosition[0] + $offsetX;
            float $newPosY = $particlePosition[1] + $offsetY;
            float $newPosZ = $particlePosition[2] + $offsetZ;
```

```
            emit -o ($selected[0]+"OFFSET") -pos $newPosX $newPosY
              $newPosZ;

        }

        $timer = `timer -e`;

        string $window = `window -title "moveWreck" -mxb 0 -mnb 0`;
        columnLayout -adjustableColumn true;
        text -label ("\nRecreated " + $particleCount + " particles in " +
          $timer + " seconds.");
        text -label ("\n(Offset by " + $offsetX + ", " + $offsetY + ", " +
          $offsetZ + ")\n");
        button -label "Close" -width 200 -height 50 -command ("deleteUI -
          window " + $window);
        showWindow;
        window -edit -widthHeight 500 125 $window;

}
```

14.2.6 cleanWreck

This tool is used to clean/remove data points from an existing Maya particle object. After selecting an existing particle object, the script creates a new particle object where points are only recreated if they are within a user-defined distance from the scene origin (coordinate value 0, 0, 0). Upon completion, a pop-up window provides information on how many of the original points were retained and the time taken to process.

```
// cleanWreck Script
// Recreate existing particle object and remove points X distance from
  origin/zero
// NOTE: Add distance in brackets (X) when running script
// Created by Dylan Gauld

global proc cleanWreck(float $checkDistance) {
```

```
string $selected[] = `ls -sl`;
int $particleCount = `getAttr ($selected[0]+".count")`;
int $j = 0;

particle -n ($selected[0]+"CLEAN");
setAttr ($selected[0]+"CLEAN.isDynamic") 0;
disconnectAttr time1.outTime
  ($selected[0]+"CLEANShape.currentTime");

float $timer = 0;
timer -s;

for ($i = 0; $i < $particleCount; ++$i) {

      float $particlePosition[] = `getParticleAttr -at position
        ($selected[0]+".pt["+$i+"]")`;
      float $xSq = `pow $particlePosition[0] 2`;
      float $ySq = `pow $particlePosition[1] 2`;
      float $zSq = `pow $particlePosition[2] 2`;
      float $rtXYZ = `sqrt ($xSq + $ySq + $zSq)`;

      if ($rtXYZ <= $checkDistance) {
            emit -o ($selected[0]+"CLEAN") -pos
              $particlePosition[0] $particlePosition[1]
              $particlePosition[2];
            $j = ($j + 1);
      }

}

$timer = `timer -e`;

string $window = `window -title "cleanWreck" -mxb 0 -mnb 0`;
columnLayout -adjustableColumn true;
text -label ("\nRecreated " + $j + " of " + $particleCount +"
  particles in " + $timer + " seconds.\n");
button -label "Close" -width 200 -height 50 -command ("deleteUI -
  window " + $window);
showWindow;
window -edit -widthHeight 400 100 $window;
```

```
}
```

14.2.7 exportWreck

This script further develops the *cleanWreck* tool by extending the calculation of the origin to one which is not positioned at 0,0,0. In addition, an updated particle object is not created and instead a new text file is written containing only the points being kept within the specified distance.

Although it was not needed as part of the research studies, the *cleanWreck and exportWreck* scripts could be used to create additional variants combining different elements - supporting an origin which is at zero or one which is not, in addition to either creating a new particle object in Maya or writing a new particle text file.

```
// exportWreck Script
// Rewrite particle text file and remove points X distance from locator
  (new origin)
// NOTE: Add distance in brackets (X) when running script
// NOTE: Requires a locator placed at the new particle object centre
  (offset from zero)
// NOTE: Does not load or create particles - creates a new TXT file after
  processing
// Created by Dylan Gauld

global proc exportWreck(float $checkDistance) {

      string $fileFilter = "XYZ files (*.xyz *.txt)";
      string $fileName[1] = `fileDialog2 -fileMode 1 -dialogStyle 2 -
        fileFilter $fileFilter`;
      $fileId = `fopen $fileName[0] "r"`;
      string $nextLine = `fgetline $fileId`;

      int $i = 0;
      int $j = 0;
```

```
string $selected[1] = `ls -sl`;
float $locatorWorldPosition[] = `xform -q -t -ws ($selected[0])`;
float $locatorWorldX = $locatorWorldPosition[0];
float $locatorWorldY = $locatorWorldPosition[1];
float $locatorWorldZ = $locatorWorldPosition[2];

$outputFilename = (`internalVar -userWorkspaceDir` + $selected[0] +
  ".txt");
$outputFile = `fopen $outputFilename "w"`;

float $timer = 0;
timer -s;

while ( size ( $nextLine ) > 0 ) {

      string $lineValues[6];
      tokenize ($nextLine, "  ,", $lineValues);
      float $lineX = $lineValues[0];
      float $lineY = $lineValues[1];
      float $lineZ = $lineValues[2];

      float $x = $lineX - $locatorWorldPosition[0];
      float $y = $lineY - $locatorWorldPosition[1];
      float $z = $lineZ - $locatorWorldPosition[2];
      float $xSq = `pow $x 2`;
      float $ySq = `pow $y 2`;
      float $zSq = `pow $z 2`;
      float $rtXYZ = `sqrt ($xSq + $ySq + $zSq)`;

      if ($rtXYZ <= $checkDistance) {
            fprint $outputFile ($lineX + " " + $lineY + " " +
              $lineZ + "\n");
            $j = ($j + 1);
      }

      $i = ($i + 1);

      $nextLine = `fgetline $fileId`;

}
```

```
        fclose $fileId;
        fclose $outputFile;

        $timer = `timer -e`;

        string $window = `window -title "exportWreck" -mxb 0 -mnb 0`;

        columnLayout -adjustableColumn true;
        text -label ("\nKept " + $j + "/" + $i +" points in " + $timer + "
          seconds.");
        text -label ("\nNew file: " + $outputFilename + " .\n");
        button -label "Close" -width 200 -height 50 -command ("deleteUI -
          window " + $window);w
        showWindow;
        window -edit -widthHeight 500 125 $window;

}
```

14.3 Appendix III: Applications for ethical approval

This appendix includes confirmation of ethical approval for two projects undertaken. The first of these (reference UOD-DJCAD-2019-0163) refers to the Troll workshops described in section 7.6, and the second application (reference UOD-DJCAD-2019-0175) sets out the expert interviews, discussed primarily in chapters 10 and 11. Both applications are included as part of this appendix.

Duncan of Jordanstone
College of Art & Design
University of Dundee

DJCAD School Research Ethics Committee

University of Dundee
Dundee
DD1 4HN

8th November 2019

Dear Dylan

Application Number: UOD-DJCAD-2019-0163

Title of Project: A practice-led exploration and development of the 3D visualisation and grading of subsea survey data

Application Number: UOD-DJCAD-2019-0175

Title of Project: SUBSEE: An exploration and development of the 3D visualisation and grading of subsea survey data

I am writing to advise you that your ethics applications have been reviewed and approved on behalf of the DJCAD School Research Ethics Committee. Approval is valid for the duration of the project, as stated in the original application.

Any changes to the approved documentation (e.g., study protocol, information sheet, consent form) must be approved by this SREC before the changes are implemented. Requests for amendments should be requested using the Post-Approval Request for an Amendment form.

Approval is valid for the duration of the project, as stated in the original application. Should you wish your study to continue beyond the stated project end date, you must request an extension to this approval a minimum of 3 months before the project end date using the Post-Approval Request for an Extension form.

Yours sincerely

Dr Sandra Wilson
Convener, DJCAD Research Ethics Committee

University of Dundee • Dundee, DD1 4HN • Scotland, UK   t: +44 (0)1382 383000   w: dundee.ac.uk
Registered Scottish Charity No: SC015096

14.3.1 Troll workshops

University of Dundee

Form A: SREC application - low risk
Version 3, 29th March 2019

Ethical Approval for Non-Clinical Research Involving Human Participants

FORM A: Application for ethical approval for low risk projects

Name of Applicant	Dylan Gauld
School	DJCAD (Art & Design)
University e-mail Address	d.z.gauld@dundee.ac.uk
Title of Project	A practice-led exploration and development of the 3D visualisation and grading of subsea survey data
Co-Investigators (with internal School or external organisational affiliation)	N/A
Projected Start Date	June 2014
Estimated End Date	January 2015
Funder (if applicable)	N/A
Version of Application (1, 2, 3…)*	1

* After revision, please update the version number before re-submission.

Students Only	
Level of Study (Undergraduate (UG); Taught Postgraduate (TPG); Research Postgraduate (RPG)	RPG (PhD)
Name of University of Dundee Supervisor	Chris Rowland (1), Jon Rogers (2)

Note: Students must copy in their supervisor when submitting the application for review.

*Page **1** of **9***

1. Project Overview

Please provide, with reference to the relevant literature, an overview of the research project providing a short explanation (maximum 400 words) of the research questions the project will address and why the study is justified.

Please write this section in a way that is accessible to a person who is not an expert in your field.

PLEASE NOTE: This is a retrospective application for research workshops which took place in 2014/15, following guidance from and a discussion with Professor Jeanette Paul earlier in 2019.

The researcher is undertaking doctoral research which uses a variety of 3D visualisation methods to present subsea survey data in new and improved ways, ultimately leading to the creation of a unique data grading system which can be used to score and compare the quality of subsea datasets against one another. This research has been informed using a set of commercial case studies, each one built upon a different real-world dataset. The researcher aims to answer the following primary research question:

> *Can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?*

This research question is addressed in greater depth using four sub-questions:

(1) *How effective are current visualisation methods in communicating subsea survey data accurately and clearly?*
(2) *What is the relationship between automation and 3D visualisation of subsea survey data?*
(3) *What are the effects on the understanding of subsea survey data in the transitioning between digital and physical 3D representations?*
(4) *What is the measurable value of innovation in 3D visualisation to the subsea surveying industry?*

As part of one case study, an interactive workshop was developed where participants could review and compare eight different methods of data visualisation, with the goal of improving the understanding of the communicative value that 3D visualisation techniques can add or remove when applied to subsea survey data. Some of these visualisation techniques are currently used commercially, while others have not yet been adopted. Comparing visualisation techniques would provide further insight into why some visualisation techniques were preferred, why some were not used, and which (if any) would be commercially viable (when considering costs incurred and time taken).

These workshops were intended to address research sub-questions 1 and 3 primarily – to improve the practical understanding and evaluation of visual communication, and to also try and identify more effective ways of presenting data in both an engaging and stimulating way (such as the use of 3D printing). It was also hoped that there would be some insight into why particular visualisation methods have not yet been adopted. This new understanding will ultimately lead to creating better visualisation outputs, resulting in the development of more useful ways of presenting, 'seeing', and interpreting subsea survey data.

2. Aims and Objectives

What are the aims and objectives of the project?

This workshop was created with the aim of investigating three specific questions:

> *Can the use of visualisation techniques improve our understanding of the underlying data?*
>
> *At what point during the visualisation process does this happen?*
>
> *Can 'over-visualising' remove this new level of understanding?*

The workshop was also intended to capture both quantitative and qualitative (multi-dimensional) data. Analysis of this resulting data proved useful in determining the visual value, if any, that was added to or removed from the data by using different methods of presenting a series of visualisation techniques, all built from a single dataset. This would later inform the commercial feasibility and relevance of each visualisation technique.

3. Research Design and Methods

Please describe the design of your study and the research methods including information about any tasks or measuring instruments (validated or otherwise) that you will be using. *If you are using non-validated instruments (e.g., surveys or questionnaires[1] you have designed, interview questions, observation protocols for ethnographic work or topic lists for unstructured data collection) please attach a copy to this ethics application.*

The researcher's methodological approach (titled **Explore Review Create** in thesis activities – and shown in accompanying document DG_Research_Methodology) is based primarily upon a combination of action research and reflective practice. The workshops formed part of a broader multi-method approach. As a result of this approach, the design of the workshops was cyclic in nature and several iterations of improvement were completed before participants were approached.

During each of the scheduled workshops, participants received an overview of the research project and an introduction to the workshop. Participation was optional, and would be entirely anonymous. Participants were presented with eight visualisation techniques – provided as seven on-screen or printed images and one 3D printed model.

[1] Please provide details of any survey tools you intend to use. The University approved online survey tool is 'Online surveys' (formerly BOS). If you intend to use a different survey tool please indicate the reason.

Each visualisation technique was briefly explained by the researcher before any responses were gathered. One of the techniques was stereoscopic and so anaglyph glasses were provided so that this could be viewed correctly. An example workshop setup can be seen in accompanying image DG_Workshop_Setup.

Eight visualisation techniques were chosen as they gave enough differentiation and clarity between each of the stages, though with not so many minor differences that it would be difficult to follow - particularly for participants who might be considered non-experts in visualisation techniques or understanding subsea survey data.

Stages one through four represent the typical steps that result in the deliverables that ADUS DeepOcean would generally provide a client. In order:

1. *Raw numerical data*
2. *Point cloud data*
3. *Processed (cleaned and subsampled) point cloud data*
4. *Interactive 3D point cloud (presented in ADUS DeepOcean's own WreckSight visualisation application).*

Stages five through eight show further development beyond the current deliverables:

5. *Surface model*
6. *Rendered surface model*
7. *Anaglyph stereoscopy*
8. *3D printed physical model.*

Full images of each of these visualisation techniques can be found in the accompanying document titled DG_Visualisation_Techniques.

Participants were asked to place a sticky note by each image as their 'vote' along a spectrum of options (providing quantitative data for direct comparison of visualisation techniques), and could also write any further thoughts that they may have had onto the sticky note (providing qualitative data for deeper analysis). The grading categories were divided into four headings: *Unclear, Understandable, Interesting, Exciting*. These were chosen by the researcher as more natural 'human' responses to visualisation, rather than disengaged and numerical choices.

Upon completion of each workshop, a series of photographs were taken to record the placement of the sticky notes alongside each of the visualisation stages (shown in accompanying image DG_Workshop_Responses). These photos included only the participant responses, and not the participants. The resulting photos were used alongside the original sticky notes to collate the results into an Excel spreadsheet – the only information recorded was the placement of each sticky note and any comments written on each sticky note, and there is no information which would later identify participants.

The workshop was conducted a total of four times, and the same approach was used throughout.

All of the resulting files (including photos and response data) were stored in the researcher's University BOX storage, and no access has been provided to anyone other than the original researcher. The files have been used to generate charts and graphics which are used in the doctoral thesis. An example of this is shown in the accompanying image DG_Workshop_Results.

4. Identification and Recruitment of Participants

How will participants be identified and recruited? Will your research involve participants outside of the UK? If so where?

Please provide details on how and by whom they will be contacted; please also add information on any exclusion criteria, should they apply. *Please attach the wording of any emails, letters, social media adverts or other written approaches that you may use for recruitment purposes.*

Participants took part in workshops based in the UK – four in total. The first three workshops were hosted as part of larger events/festivals, and the fourth (Fife Council) was arranged as a 'lunch-time lecture' style event.

Small Society Lab (June 2014) – a range of academics and researchers, with mixed experience of 3D computer graphics.

Edinburgh Napier University (October 2014) – digital media students, who have studied 3D computer graphics and animation techniques.

Mozilla Festival (October 2014) – a wide variety of (mostly unknown) participants, likely to include designers, researchers, technologists and members of the public.

Fife Council (January 2015) – a group of professionals with little-to-no knowledge of 3D computer graphics, visualisation or subsea survey data.

Each workshop was arranged in advance, and participants chose to attend and take part knowing that their responses would be recorded anonymously for research purposes.

There were no exclusion criteria specified for any of the workshops.

Due to the nature of the workshop data recorded, there is no way to identify participants after each event.

5. Informed Consent

How will you obtain informed consent? Are you satisfied that all participants have capacity to make their own decisions and understand the risks?

Please explain how and when participants will be informed about the scope of the research, what their involvement would entail and their rights under data protection legislation. *Please provide the participant information sheet and consent form with this application*; if consent is not obtained in written format (e.g., oral communication, deliberate action to opt-in to surveys or questionnaires), please provide details of how consent will be obtained and recorded. If the project involves photography or video- or audio-recording of participants, explicit consent will need to be given; where applicable this includes consent for someone not on the direct research team to have access to the participant's data (e.g. for transcription). Explain how you have considered and will address consent for the preservation and potential sharing and reuse of data.

At the beginning of each workshop, participants were briefed on the ongoing research, the workshop particulars, and how their responses would be recorded and used. Participants were also advised that any responses would be stored securely, and only for as long as necessary (the duration of the PhD research).

All of the participants were advised that taking part was optional, and anonymous, and consent was implied in continuing to provide responses via the sticky notes. This consent was informed by the briefing at the start of each session, and additionally by the presence of the researcher who could answer questions and provide further assistance if required.

As the workshops took place in academic or professional environments, it is not expected that there were any vulnerable participants. There are no also no risks associated with the workshops and related research outputs.

Photographs were taken to record user responses, but care was taken so that no participants were included in these images. No video or audio recording was undertaken.

It is not expected that the resulting response data will be shared or re-used beyond the scope of the doctoral research and any associated publications.

6a. Data Management: Lawful Processing of Data

Data protection legislation[2] requires participants to be informed of the lawful basis for processing their personal data. At the University of Dundee, the normal basis for the lawful processing of personal data in research is that 'processing is necessary for the performance of a task carried out in the public interest or in the exercise of official authority vested in the controller'. If you intend to use another lawful basis you must contact the University's Data Protection Officer (DPO) for advice and insert the lawful basis agreed with the DPO below.

Workshop participants were informed that their responses would be processed and stored safely and securely. No personal data (including photographs) was gathered. At the time of the workshops being hosted, Data Protection Act 1998 provided assurances on obtaining, processing and using personal data.

6b. Data Management: Planning

2 The General Data Protection Regulation ((EU) 2016/679) and the UK Data Protection Act (2018). Further information can be obtained from the University of Dundee data protection website and the website of the Information Commissioner's Office.

Please describe your plan for managing the data[3] you will collect during your project and how it complies with data protection legislation. Include information on:

i) The type and volume of data; ii) Where and for how long will the data be stored and what measures will be in place to ensure secure storage; iii) Whether the data will be anonymised or pseudonymised[4]; iv) How secure access will be provided to data for collaborators; v) Whether and how data will be shared for reuse by other researchers beyond the project (including details on any access restrictions); vi) Processes in place to erase and/or stop processing an individual participant's data (except where this would render impossible or seriously impair the research objectives)[5]; vii) Processes in place for individuals to have inaccurate personal data rectified, or completed if it is incomplete; viii) Who has overall responsibility for data management for the research project; ix) Arrangements for collection and transfer of data outside the UK.

Resulting response data is stored as a series of image files and Excel spreadsheet files.

All data is stored in the researcher's University BOX storage (as advised to do), and will be held for the duration of the PhD studies and whilst any related publications are developed. Access to these files has not been shared beyond the original researcher.

All data has been anonymised.

There are no data collaborators - no shared access has been enabled.

There are no plans to share the data for re-use by other researchers beyond the project.

There are no processes in place to erase or stop processing of an individual participants data, as no identifying or personal information has been recorded.

There are no processes in place for individuals to have inaccurate personal data rectified or completed, as no identifying or personal information has been recorded.

The researcher maintains sole responsibility for data management for this data project.

There are no arrangements for collection and transfer of data outside the UK, as this is not expected to happen.

7. Other Permissions

3 Note that staff and postgraduate research students are required to complete a research data management plan under the University of Dundee's Policy to Govern the Management of Research Data. However, providing you have included the information requested above, it is not necessary to attach a formal data management plan to this application.

4 (Article 4(5) of the General Data Protection Regulation describes pseudonymisation as: "The processing of personal data in such a way that the data can no longer be attributed to a specific data subject without the use of additional information". An example would be where a coded reference or pseudonym is substituted for personally identifiable data.

5 The right to erasure under the General Data Protection Regulation does not apply if erasing the data would prejudice scientific or historical research, or archiving that is in the public interest.

Are any other permissions (e.g., from local authorities) required? If so which?

No other permissions were required.

8. Risks of Harm to Researchers and Participants

Risks of harm. Please detail any risks associated with the project. Does the research involve fieldwork (either in the UK or overseas)? Does the research incur a risk of injury or ill-health above the level of risk prevalent in daily living? *If yes, please complete the relevant risk assessment form(s) (general risk assessment form and/or the risk assessment for Travelling on University Work Overseas) and submit with this application.*

There are no risks of harm, injury or ill-health associated with these workshops – for either the researcher or participants.

9. Other Ethical Considerations

Are there any other ethical considerations relating to your project which have not been covered above? If so, please explain.

10. Documentation

Please list all attached documentation, ensuring that each item has a date and version number.

DG_Research_Methodology_v1_290819
DG_Visualisation_Techniques_v1_290819
DG_Workshop_Responses_v1_290819
DG_Workshop_Results_v1_290819
DG_Workshop_Setup_v1_290819

11. Declaration

By signing below I declare that I have read the University Code of Practice for Non-Clinical Research Ethics on Human Participants and that my research abides by these guidelines. I understand that this application and associated documents will be retained by the University.

Principal Investigator or Student

Name: Dylan Gauld Date: 29/08/2019

Signature:

Supervisor (for applications from students)

Name: Date: 09/09/19

Signature:

14.3.2 Expert interviews

University of Dundee

Form A: SREC application - low risk
Version 3, 29th March 2019

Ethical Approval for Non-Clinical Research Involving Human Participants

FORM A: Application for ethical approval for low risk projects

Name of Applicant	Dylan Gauld
School	DJCAD (Art & Design)
University e-mail Address	d.z.gauld@dundee.ac.uk
Title of Project	SUBSEE: An exploration and development of the 3D visualisation and grading of subsea survey data
Co-Investigators (with internal School or external organisational affiliation)	N/A
Projected Start Date	October 2019
Estimated End Date	November 2019
Funder (if applicable)	
Version of Application (1, 2, 3…)*	1

* After revision, please update the version number before re-submission.

Students Only	
Level of Study (Undergraduate (UG); Taught Postgraduate (TPG); Research Postgraduate (RPG)	RPG (PhD)
Name of University of Dundee Supervisor	Chris Rowland (1), Jon Rogers (2)

Note: Students must copy in their supervisor when submitting the application for review.

*Page **1** of **8***

1. Project Overview

Please provide, with reference to the relevant literature, an overview of the research project providing a short explanation (maximum 400 words) of the research questions the project will address and why the study is justified.

Please write this section in a way that is accessible to a person who is not an expert in your field.

High-resolution subsea surveying offers new opportunities to explore difficult or hazardous underwater environments and, when using multi-beam sonar, provides three-dimensional bathymetric data for visualisation. The primary focus of this doctoral research is whether the 3D visualisation and grading of subsea survey data can be developed beyond current industry practices, where there is very little existing research in this area.

This work is being directed by a primary research question - ***can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?***

This question has been broken down into four sub-questions to be addressed:

(1) *How effective are current visualisation methods in communicating subsea survey data accurately and clearly?*
(2) *What is the relationship between automation and 3D visualisation of subsea survey data?*
(3) *What are the effects on the understanding of subsea survey data in the transitioning between digital and physical 3D representations?*
(4) *What is the measurable value of innovation in 3D visualisation to the subsea surveying industry?*

Three commercial case studies and their resulting datasets have been used to create and evaluate the application of a variety of 3D visualisation techniques, including some which go beyond those readily adopted in the offshore industry such as the use of 3D printing. Based on these case studies, the researcher identified three key outcomes – improved knowledge of which visualisation techniques offer the best communicative value, the creation of new subsea visualisation tools, and a lack of consistency in evaluating or grading subsea survey datasets.

The researcher proposes that the work undertaken during each of these three case studies provides new insight into improving the visualisation of subsea survey data by applying 3D visualisation techniques. As a result of this new knowledge, the DUNDEE DATA GRADING SCALE, which can be used to grade subsea survey datasets, has been created as a first step towards improving data capture and quality awareness. It is expected that this will provide a greater understanding of what will be required to produce quality 3D visualisations from future datasets, with increased clarity in how to achieve this improvement by applying a range of developing visualisation tools.

As this project is joint-funded by a commercial company, this research study will provide evaluation and improvement of these research outcomes by gathering views and opinions (via written questionnaire) from industry experts.

2. Aims and Objectives

What are the aims and objectives of the project?

The aim of this research questionnaire is to evaluate the research outcomes which were generated whilst undertaking three commercial case studies, for presentation in a doctoral thesis.

The questionnaire has four objectives:

A) To identify why the participant is best placed as an industry expert

B) To better understand the use of 3D visualisation techniques and current practices in industry

C) To clarify and better define *good* and *bad* subsea survey data

D) To evaluate and improve the DUNDEE DATA GRADING SCALE

3. Research Design and Methods

Please describe the design of your study and the research methods including information about any tasks or measuring instruments (validated or otherwise) that you will be using. *If you are using non-validated instruments (e.g., surveys or questionnaires you have designed, interview questions, observation protocols for ethnographic work or topic lists for unstructured data collection) please attach a copy to this ethics application.*

The researcher's methodological approach (titled **Explore Review Create** in thesis activities – and shown in accompanying document DG_Research_Methodology) is based primarily upon case study research, action research and reflective practice. The questionnaire to be used in this research study forms one of the evaluation methods employed, and offers the opportunity to conduct written 'interviews' with industry professionals. The final version of the written questionnaire is attached to this application (titled SUBSEE_Questionnaire).

Written questionnaires, in Microsoft Word format, were selected as the most appropriate method under the circumstances. Due to the nature of the offshore industry, many professionals regularly undertake fieldwork, and often spend time with unreliable or no internet access. The participants can download the questionnaire and then complete it in their own time, with no online access required. This can then be returned when regular internet access is resumed.

It is expected that the questionnaire will take around 30 minutes for participants to complete, and they can do this remotely and in their own time.

There are no requirements for participants to attend any scheduled sessions or undertake any travel to complete this study.

There are no rewards or payments for those taking part in this study.

The following types of personal data are being collected: participant's name, email address, and views and opinions. No special category (sensitive personal) data is being collected. Data will be held digitally on secure servers managed by Box on behalf of the University of Dundee. Box adheres to the highest industry standards of security and is suitable for storing University information that falls within private and confidential classifications.

All responses will be anonymised before being published, and this is explained in both the Participant Information Sheet and questionnaire document.

The resulting anonymised data will be used to inform the evaluation and analysis undertaken as part of the researcher's doctoral studies (in the form of direct quotes and the creation of graphs and charts), to end no later than 29th May 2020, after which any stored participant data will be erased.

4. Identification and Recruitment of Participants

How will participants be identified and recruited? Will your research involve participants outside of the UK? If so where?

Please provide details on how and by whom they will be contacted; please also add information on any exclusion criteria, should they apply. *Please attach the wording of any emails, letters, social media adverts or other written approaches that you may use for recruitment purposes.*

The experts who will be participants in this research study have already been identified, and have been selected for their familiarity with subsea survey data and/or experience working as part of the offshore surveying industry. These participants were identified by the researcher whilst undertaking commercial placements which would later become case studies in the doctoral thesis.

Participants will be contacted by the researcher directly, via email, and will be sent the Participant Information Sheet, Informed Consent form, and SUBSEE questionnaire (attached documents titled ParticipantInformationSheet, InformedConsent, and SUBSEE_Questionnaire).

In selecting these participants, there were no specific exclusion criteria. Participants were included based on their relevant industry experiences.

Each of the selected participants operates on a worldwide basis but is based within the UK.

5. Informed Consent

How will you obtain informed consent? Are you satisfied that all participants have capacity to make their own decisions and understand the risks?

Please explain how and when participants will be informed about the scope of the research, what their involvement would entail and their rights under data protection legislation. *Please provide the participant information sheet and consent form with this application*; if consent is not obtained in written format (e.g., oral communication, deliberate action to opt-in to surveys or questionnaires), please provide details of how consent will be obtained and recorded. If the project involves photography or video- or audio-recording of participants, explicit consent will need to be given; where applicable this includes consent for someone not on the direct research team to have access to the participant's data (e.g. for transcription). Explain how you have considered and will address consent for the preservation and potential sharing and reuse of data.

Participants will be provided with a Participant Information Sheet and Informed Consent form. Informed consent will be obtained by each participant signing (or typing) their name and returning the Informed Consent form alongside their completed questionnaire. Anonymity and confidentiality are explained as part of the Participant Information Sheet.

The Participant Information Sheet explains that participation in this research study is voluntary, and that participants may choose to withdraw from the study at any time, without explanation and without penalty, by contacting either the principal researcher or academic supervisor.

There are no vulnerable participants, and each identified participant has the capacity to make their own decisions. There are no known risks associated with this research study, and this is explained in the Participant Information Sheet.

This research study does not involve the photography or video- or audio-recording of participants.

The collected data will be stored securely and there will be no unauthorised access beyond that of the researcher. The collected data will only be used for the purposes of this research study and will not be used for any other purposes.

There are no specific debriefing plans for participants, though the Participant Information Sheet provides information on how their questionnaire responses will be used, and how they can view any related published material.

6a. Data Management: Lawful Processing of Data

Data protection legislation requires participants to be informed of the lawful basis for processing their personal data. At the University of Dundee, the normal basis for the lawful processing of personal data in research is that 'processing is necessary for the performance of a task carried out in the public interest or in the exercise of official authority vested in the controller'. If you intend to use another lawful basis you must contact the University's Data Protection Officer (DPO) for advice and insert the lawful basis agreed with the DPO below.

Data protection statements (GDPR) provided by the University of Dundee have been included as part of the Participant Information Sheet.

6b. Data Management: Planning

Please describe your plan for managing the data you will collect during your project and how it complies with data protection legislation. Include information on:

i) The type and volume of data; ii) Where and for how long will the data be stored and what measures will be in place to ensure secure storage; iii) Whether the data will be anonymised or pseudonymised; iv) How secure access will be provided to data for collaborators; v) Whether and how data will be shared for reuse by other researchers beyond the project (including details on any access restrictions); vi) Processes in place to erase and/or stop processing an individual participant's data (except where this would render impossible or seriously impair the research objectives); vii) Processes in place for individuals to have inaccurate personal data rectified, or completed if it is incomplete; viii) Who has overall responsibility for data management for the research project; ix) Arrangements for collection and transfer of data outside the UK.

The collected data will be in the form of written questionnaires (Microsoft Word format), and is expected to be gathered from 3-5 participants in total. After the questionnaires have been completed and returned, these will be anonymised - anonymity and confidentiality are explained as part of the Participant Information Sheet.

The data will be held digitally on secure servers managed by Box on behalf of the University of Dundee. Only the principal researcher will have authorisation to access the study data, and the data will be held in this way until the end of the researcher's doctoral studies (no later than 29th May 2020) before being erased.

There are no arrangements in place for data sharing or re-use of data by other researchers beyond this project, as information collected is specific to this study and evaluation - it will be used for the purposes of this research study only and will not be used for any other purposes.

If a participant wishes to withdraw from the study, they can request this by contacting the researcher and any processing of their data will be stopped and their information will be erased from the secure storage. If a participant wishes to have inaccurate personal data rectified, or completed if it is incomplete, they can contact the researcher directly – contact details for both the researcher and academic supervisor are provided as part of the Participant Information Sheet and Informed Consent form.

The Participant Information Sheet makes it clear that the primary contact is the researcher, and that the University of Dundee is the data controller.

There are no arrangements for the collection and transfer of data outside of the UK, as data is being collected and processed within the UK.

7. Other Permissions

Are any other permissions (e.g., from local authorities) required? If so which?

N/A

8. Risks of Harm to Researchers and Participants

Risks of harm. Please detail any risks associated with the project. Does the research involve fieldwork (either in the UK or overseas)? Does the research incur a risk of injury or ill-health above the level of risk prevalent in daily living? *If yes, please complete the relevant risk assessment form(s) (general risk assessment form and/or the risk assessment for Travelling on University Work Overseas) and submit with this application.*

There are no known risks associated with this project, either to researchers or participants.

9. Other Ethical Considerations

Are there any other ethical considerations relating to your project which have not been covered above? If so, please explain.

N/A

10. Documentation

Please list all attached documentation, ensuring that each item has a date and version number.

DG_Research_Methodology_v1_021019
InformedConsent_v1_021019
ParticipantInformationSheet_v1_021019
SUBSEE_Questionnaire_v1_021019

11. Declaration

By signing below I declare that I have read the University Code of Practice for Non-Clinical Research Ethics on Human Participants and that my research abides by these guidelines. I understand that this application and associated documents will be retained by the University.

Principal Investigator or Student

Name: Dylan Gauld Date: 02/10/19

Signature:

Supervisor (for applications from students)

Name: Date:

Signature:

Informed Consent for

SUBSEE: AN EXPLORATION AND DEVELOPMENT OF THE 3D VISUALISATION AND GRADING OF SUBSEA SURVEY DATA

1. Taking part in the study

	YES	NO
I have read the Participant Information Sheet, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.		
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time during data collection, without having to give a reason.		
I understand that taking part in the study involves answering a series of questions in the form of a written questionnaire.		

2. Use of information in the study

I understand that the information I provide will be used for the purposes of this research study only and will not be used for any other purposes.		
I understand that personal information collected about me that can identify me, such as my name or where I live, will not be shared beyond the study team.		
I agree that anonymised direct quotes can be used in research outputs.		

3. Signatures

____________________ ______________________________ _________

Participant's Name Participant's Signature Date

By signing (or typing your name) above, you are indicating that you have read and understood the Participant Information Sheet and that you agree to take part in this research study.

____________________ ______________________________ _________

Name of Researcher Signature of Researcher Date

4. Study contact details for further information

Dylan Gauld, PhD Researcher
Duncan of Jordanstone College of Art & Design, University of Dundee
Email: d.z.gauld@dundee.ac.uk

5. Alternative formats

If you require a copy of the Participant Information Sheet or Consent Form in alternative formats (e.g. large print or Braille), please email the study contact directly for further information.

1 of 1

Participant Information Sheet for

SUBSEE: AN EXPLORATION AND DEVELOPMENT OF THE 3D VISUALISATION AND GRADING OF SUBSEA SURVEY DATA

You are invited to take part in a research project. Before you decide whether or not you would like to participate it is important that you read the information provided below. This will help you to understand why and how the research is being carried out and what participation will involve. Please let the researcher who gave you this information know if anything is unclear or you have any questions.

Who is conducting the research?

This research is being conducted by the principal researcher, Dylan Gauld (d.z.gauld@dundee.ac.uk), as part of ongoing doctoral studies at the University of Dundee, and is being supervised by Professor Chris Rowland (c.rowland@dundee.ac.uk).

Who is funding the research?

This research is joint-funded by the Engineering and Physical Sciences Research Council (EPSRC) and ADUS DeepOcean.

What is the purpose of the research?

High-resolution subsea surveying offers new opportunities to explore difficult or hazardous underwater environments and, when using multi-beam sonar, provides three-dimensional bathymetric data for visualisation. The primary focus of this research is whether the 3D visualisation and grading of subsea survey data can be developed beyond current industry practices. This work is being directed by one key research question - *can the communication and understanding of subsea survey data be improved by using 3D visualisation methods?*

Three commercial case studies and their resulting datasets have been used to create and evaluate the application of a variety of 3D visualisation techniques, including some which go beyond those readily adopted in the offshore industry such as the use of 3D printing. Based on these case studies, the researcher identified three key outcomes – improved knowledge of which visualisation techniques offer the best communicative value, the creation of new subsea visualisation tools, and a lack of consistency in evaluating or grading subsea survey datasets.

The researcher proposes that the work undertaken during each of these three case studies provides new insight into improving the visualisation of subsea survey data by applying 3D visualisation techniques. As a result of this new knowledge, the DUNDEE DATA GRADING SCALE, which can be used to grade subsea survey datasets, has been created as a first step towards improving data capture and quality awareness. It is expected that this will provide a greater understanding of what will be required to produce quality 3D visualisations from future datasets, with increased clarity in how to achieve this improvement by applying a range of developing visualisation tools. This research study will provide evaluation and improvement of these research outcomes by gathering views and opinions from industry experts.

Why have I been invited to take part?

You have been invited to take part because of your experience working with subsea survey data and/or as part of the offshore surveying industry.

Do I have to take part?

Participation in this research study is voluntary. You may choose to withdraw from the study at any time, without explanation and without penalty, by contacting either the researcher or academic supervisor by email.

What will happen if I take part?

You will be sent a questionnaire by email (provided as an editable Microsoft Word file). This questionnaire asks a series of questions related to subsea survey data and 3D visualisation, and is expected to take around 30 minutes to complete. Your written responses will be anonymised after you return the questionnaire to the researcher by email, ready to be included as part of the ongoing doctoral research and evaluation.

Are there any risks in taking part?

There are no known risks identified for participants in this study.

What are the possible benefits of taking part?

There are no direct rewards or compensations available for taking part in this study. Your responses will contribute to ongoing research at the University of Dundee and potentially offer improvement to current subsea surveying industry practices and guidance.

Will my taking part in this project be kept confidential?

All information that you provide as part of this research study will be kept confidential. Access to your information is restricted to authorised users (the researcher only), and your information will not be transferred or shared with other individuals or organisations. Your responses will be anonymised by the researcher to ensure your responses do not allow you to be identified.

What will happen to the information I provide?

The information that you provide will be held digitally on secure servers managed by Box on behalf of the University of Dundee. Box adheres to the highest industry standards of security and is suitable for storing University information that falls within private and confidential classifications. Your information will be stored for the duration of this doctoral research (no later than 29th May 2020) and will not be transferred or re-used beyond this research study. Should you decide to withdraw from the research study, your information will be erased upon doing so.

Your responses will be anonymised before any publication, and the results of the research will be published in a doctoral thesis which will be made publicly available after any specified embargo period. At such a time, participants can access a copy of the published thesis from the University's online research portal, Discovery (https://discovery.dundee.ac.uk/en/). Prior to the embargo period ending, access can be granted by direct request to the researcher, subject to any funder or publisher requirements.

Data Protection

As part of this research study, the only personal data that will be collected and processed are your name, you email address, and your views and opinions. No special category (sensitive personal) data will be collected or processed. Data is collected and processed in accordance with the General Data Protection Regulation (GDPR).

The University asserts that it lawful for it to process your personal data in this project as the processing is necessary for the performance of a task carried out in the public interest or in the exercise of official authority vested in the controller.

The University of Dundee is the data controller for the personal and/or special categories of personal data processed in this project. The University respects your rights and preferences in relation to your data and if you wish to update, access, erase, or limit the use of your information, please let us know. Please note that some of your rights may be limited where personal data is processed for research, but we are happy to discuss that with you.

If you wish to complain about the use of your information please contact the University's Data Protection Officer in the first instance (dataprotection@dundee.ac.uk). You may also wish to contact the Information Commissioner's Office (https://ico.org.uk/). You can find more information about the ways that personal data is used at the University at: https://www.dundee.ac.uk/information-governance/dataprotection/.

Is there someone else I can complain to?

If you wish to complain about the way the research has been conducted please contact the Convener of the University Research Ethics Committee (https://www.dundee.ac.uk/research/ethics/contacts/).

Alternative formats

If you require a copy of the Participant Information Sheet or Consent Form in alternative formats (e.g. large print or Braille), please email the study contact directly for further information.

Study contact details for further information

Dylan Gauld, PhD Researcher
Duncan of Jordanstone College of Art & Design, University of Dundee
Email: d.z.gauld@dundee.ac.uk

14.4 Appendix IV: Expert interviews

This appendix includes the completed online interviews referred to within the thesis. Images have been removed from each returned document, as the purpose of this section is to present the responses provided by the invited experts, and the original images can be found elsewhere within the thesis. The Dundee Data Grading Scale is shown in Figure 10.6, and the seven stages of visualisation presented in the interview document are shown in the following figures:

- Figure 7.12 (*raw data*)
- Figure 7.13 (*point cloud*)
- Figure 7.14 (*processed point cloud*)
- Figure 7.15 (*WreckSight*)
- Figure 7.16 (*digital surface model*)
- Figure 7.18 (*stereoscopic render*)
- Figure 7.19 (*3D printed physical model*)

14.4.1 Expert A

A1 Which of the following areas have you had direct experience working with? *(Please select all that apply.)*

	Computer graphics and animation
	Making (e.g. laser cutting or 3D printing)
X	3D visualisation
X	Subsea survey data (e.g. acquisition, processing, etc.)

A2 Please can you provide information on your roles/experiences related to this research and why you are best placed as an industry expert (e.g. hydrographic surveyor for 10 years, etc.)?

I am a researcher and software developer who has previously contributed to the development of custom 3D visualisation software for use in the marine

salvage industry. I have been involved in this field since 2008. I continue to support, through software development, ongoing research into visualising historic shipwrecks.

B1 Which of these different visualisation stages do you **regularly** see provided as client deliverables? *(Please tick all that apply.)*

X	Raw data
X	Point cloud
X	Processed point cloud
X	WreckSight
	Digital surface model
	Stereoscopic render
	3D printed physical model

B2 Which of these different visualisation stages do you think is the **most expensive solution,** considering factors such as equipment hire, human resources and project duration? *(Please rank each option using numbers 1 through 7, with 1 being the most expensive, and 7 being the least.)*

7	Raw data
6	Point cloud
5	Processed point cloud
4	WreckSight
3	Digital surface model
2	Stereoscopic render
1	3D printed physical model

B3 Which of these different visualisation stages do you think offers the **greatest communicative value**, considering factors such as clarity, accuracy and realism? *(Please rank each option using numbers 1 through 7, with 1 offering the greatest communicative value, and 7 offering the least.)*

7	Raw data
6	Point cloud
4	Processed point cloud
2	WreckSight
3	Digital surface model
5	Stereoscopic render
1	3D printed physical model

B4 Which of these different visualisation stages would you like to see used **more** often as deliverables and why? *(Please select any that apply and provide further information on your reasons for these choices in the text box below.)*

	Raw data
	Point cloud
x	Processed point cloud
x	WreckSight
	Digital surface model
	Stereoscopic render
	3D printed physical model

Although WreckSight is a bespoke format the underlying method offers an aesthetically considered representation of the data which has been shown to have strong communicative capability and is also metrically accurate when given reliable input data.

The processed point cloud deliverable is a useful starting point for further visualisation treatment.

B5 Which of these different visualisation stages would you like to see used **less** often as deliverables and why? *(Please select any that apply and provide further information on your reasons for these choices in the text box below.)*

x	Raw data
x	Point cloud
	Processed point cloud
	WreckSight
	Digital surface model
	Stereoscopic render
	3D printed physical model

Raw data is of limited use in constructing the types of end user solutions that I am involved with as it requires significant additional processing, often manual, before a useful visualisation output can be produced. I would like to see less use of unprocessed point clouds for the same reason.

C1 What attributes or features do you think define **good quality** subsea survey data?

Metric accuracy, low noise, consistent point density, high point density, location accuracy, oblique coverage (i.e. not just top-down capture), detail

C2 What attributes or features do you think define **bad quality** subsea survey data?

Excessive noise, poor or inconsistent coverage

C3 What are the biggest challenges you face when working with subsea survey data?

Noise removal, identifying features within the data, accurate data registration

D1 Are you aware of any guidance on best practice, including the use of metadata or paradata, when working with subsea survey data? *(If 'yes', please provide details.)*

	Yes
x	No

D2 Are you aware of any activities or standards currently used to grade or evaluate subsea survey data? *(If 'yes', please provide details.)*

	Yes
x	No

D3 How does the *Dundee Data Grading Scale* compare to other means of grading subsea survey data that you have previously used? *(If you haven't used any others, please write N/A.)*

N/A

D4 The *Dundee Data Grading Scale* is designed to make it easier to identify and compare the quality of subsea survey datasets. On a scale of 1 to 5, how well do you think this has been achieved? *(Please provide further information on your reasons for this choice in the text box below.)*

	1 *(not at all achieved)*
	2
	3
	4
x	5 *(fully achieved)*

This appears to be a sensible and useful approach to data grading

D5 What do you think are the **advantages** and **disadvantages** of using the *Dundee Data Grading Scale* to grade and compare subsea survey datasets?

A disadvantage would be the possibility of ruling out data which scores low on the grading system – I believe it is important to be open to the possibility of using lower quality or incomplete data under certain circumstances as with additional work acceptable visualisation results may still be achieved. A clear advantage would be to inform the cost of producing a data visualisation.

D6 What do you think of the **selection**, **ordering** and **relevance** of the grading criteria used by the *Dundee Data Grading Scale*? Are there any that you would change?

I would not alter the grading criteria.

D7 How would you **improve** the *Dundee Data Grading Scale*?

For the use case of exposition of historic subsea sites (which my work is often associated with) the selection criteria may be different to IMR because the acquisition methods may also be different. For example subsea photogrammetry may not provide absolute location and scale information, nor wide coverage, but excels at capturing a high level of detail and realism. Therefore one potential improvement may be to consider alternate use cases and offer grading pathways which reflect these. However for salvage and IMR purposes I think the scheme as proposed would serve these applications well.

14.4.2 Expert B

A1 Which of the following areas have you had direct experience working with? *(Please select all that apply.)*

	Computer graphics and animation
	Making (e.g. laser cutting or 3D printing)
yes	3D visualisation
yes	Subsea survey data (e.g. acquisition, processing, etc.)

A2 Please can you provide information on your roles/experiences related to this research and why you are best placed as an industry expert (e.g. hydrographic surveyor for 10 years, etc.)?

Over 25 years' experience in maritime related sectors, mainly with salvage and wreck removal, offshore renewables, oil and gas, defence and maritime archaeology. Original co-founder of ADUS (Advanced Underwater Surveys Ltd. in 2006, latterly ADUS Deepocean Ltd.), which specialised in subsea 3D data acquisition and visualisation. Extensive experience in marine forensics and maritime digitalisation; undertaken notable work around the world, including high profile cases such the Deepwater Horizon oil rig, the Costa Concordia, the B159 Russian nuclear submarine, the Rena, the Oliva, the Baltic Ace, the Thurco Cloud and the Sewol ferry, amongst others.

B1 Which of these different visualisation stages do you **regularly** see provided as client deliverables? *(Please tick all that apply.)*

	Raw data
	Point cloud
yes	Processed point cloud
	WreckSight
yes	Digital surface model
	Stereoscopic render
	3D printed physical model

B2 Which of these different visualisation stages do you think is the **most expensive solution,** considering factors such as equipment hire, human resources and project duration? *(Please rank each option using numbers 1 through 7, with 1 being the most expensive, and 7 being the least.)*

7	Raw data
6	Point cloud
5	Processed point cloud
4	WreckSight
1	Digital surface model
3	Stereoscopic render
2	3D printed physical model

B3 Which of these different visualisation stages do you think offers the **greatest communicative value**, considering factors such as clarity, accuracy and realism? *(Please rank each option using numbers 1 through 7, with 1 offering the greatest communicative value, and 7 offering the least.)*

7	Raw data
6	Point cloud
3	Processed point cloud
4	WreckSight
1	Digital surface model
2	Stereoscopic render
5	3D printed physical model

B4 Which of these different visualisation stages would you like to see used **more** often as deliverables and why? *(Please select any that apply and provide further information on your reasons for these choices in the text box below.)*

	Raw data
	Point cloud
yes	Processed point cloud
	WreckSight
yes	Digital surface model

	Stereoscopic render
	3D printed physical model

Point clouds have traditionally not been supplied as a deliverable because of client's inability to readily access and utilise in various other proprietary 3D software. This is changing with Web based solutions such as GISGRO and Skyline, which are 3D GIS systems. Processed point clouds derived from tightly controlled survey can be considered 'As Is' models and are more valuable compared with 'As Built' models derived from existing plans etc; Much easier these days to utilise processed point clouds directly as client deliverable using GISGRO or Skyline; Digital surface models (accompanied with appropriate metrics describing how well they match with the point clouds they have been derived from) have wider uses: for example within offshore simulation (osc.no);

B5 Which of these different visualisation stages would you like to see used **less** often as deliverables and why? *(Please select any that apply and provide further information on your reasons for these choices in the text box below.)*

	Raw data
	Point cloud
	Processed point cloud
	WreckSight
	Digital surface model
yes	Stereoscopic render
	3D printed physical model

Stereoscopic not used much in my experience – especially as VR is now much more accessible (iQ3 for example, and Skyline, Cloud Compare);

C1 What attributes or features do you think define **good quality** subsea survey data?

High Accuracy (where required) High Precision High Data density; Limited noise; Controlled acquisition; Good visualisation;

C2 What attributes or features do you think define **bad quality** subsea survey data?

Inaccuracy or low precision; Low data density; High noise; Uncontrolled acquisition: multiple passed binned for e.g.; Limited meta data; Inappropriate visualisation

C3 What are the biggest challenges you face when working with subsea survey data?

Determining appropriate acquisition methodology for the task – ie laser, sonar, photogrammetry; Positioning and motion reference; Interfacing & equipment failure (redundancy) Appropriate platform for equipment deployment; Speed of post processing File sizes Managing client expectations;

D1 Are you aware of any guidance on best practice, including the use of metadata or paradata, when working with subsea survey data? *(If 'yes', please provide details.)*

yes	Yes
	No

In house procedures

D2 Are you aware of any activities or standards currently used to grade or evaluate subsea survey data? *(If 'yes', please provide details.)*

Yes	Yes
	No

In house: most companies would have their own procedures & QA ; also metrics derived from processing software: i.e. total propagated error,

D3 How does the *Dundee Data Grading Scale* compare to other means of grading subsea survey data that you have previously used? *(If you haven't used any others, please write N/A.)*

N/A

D4 The *Dundee Data Grading Scale* is designed to make it easier to identify and compare the quality of subsea survey datasets. On a scale of 1 to 5, how well do you think this has been achieved? *(Please provide further information on your reasons for this choice in the text box below.)*

	1 *(not at all achieved)*
	2
X	3
	4
	5 *(fully achieved)*

This is too linear, and apparently limited to datasets derived from MBES or laser sensors which require positioning and orientation. How would point cloud datasets derived from photogrammetry fit into this grading process – where completely relative models can be derived from image processing alone – to be scaled and positioned at a later stage?

D5 What do you think are the **advantages** and **disadvantages** of using the *Dundee Data Grading Scale* to grade and compare subsea survey datasets?

This is useful – but too simplistic. It doesn't consider the end requirement – i.e. the reason for the acquisition of the survey data: i.e. is this general bathymetry data or for Metrology? The latter would have far higher standard of accuracy required for the deliverables.

How are you considering if datasets are complete?

What resolution does the survey require?

What tolerances does the survey require? Accuracy for accuracy's sake: this has a significant commercial impact.

D6 What do you think of the **selection**, **ordering** and **relevance** of the grading criteria used by the *Dundee Data Grading Scale*? Are there any that you would change?

See above

D7 How would you **improve** the *Dundee Data Grading Scale*?

See above

14.4.3 Expert C

A1 Which of the following areas have you had direct experience working with? *(Please select all that apply.)*

	Computer graphics and animation
Y	Making (e.g. laser cutting or 3D printing)
Y	3D visualisation
Y	Subsea survey data (e.g. acquisition, processing, etc.)

A2 Please can you provide information on your roles/experiences related to this research and why you are best placed as an industry expert (e.g. hydrographic surveyor for 10 years, etc.)?

Hydrographic survey at ADUS. Also now founder and director of industry leading subsea 3D survey company Ultrabeam Hydrographic.

B1 Which of these different visualisation stages do you **regularly** see provided as client deliverables? *(Please tick all that apply.)*

Y	Raw data (but this data is never viewed it is just so the client has a copy)
	Point cloud
Y	Processed point cloud
	WreckSight
Y	Digital surface model
	Stereoscopic render
	3D printed physical model

B2 Which of these different visualisation stages do you think is the **most expensive solution,** considering factors such as equipment hire, human resources and project duration? *(Please rank each option using numbers 1 through 7, with 1 being the most expensive, and 7 being the least.)*

7	Raw data
6	Point cloud
5	Processed point cloud
4	WreckSight
3	Digital surface model
2	Stereoscopic render
1	3D printed physical model

B3 Which of these different visualisation stages do you think offers the **greatest communicative value**, considering factors such as clarity, accuracy and realism? *(Please rank each option using numbers 1 through 7, with 1 offering the greatest communicative value, and 7 offering the least.)*

7	Raw data
6	Point cloud
4	Processed point cloud
2	WreckSight
1	Digital surface model
3	Stereoscopic render
5	3D printed physical model

B4 Which of these different visualisation stages would you like to see used **more** often as deliverables and why? *(Please select any that apply and provide further information on your reasons for these choices in the text box below.)*

	Raw data
	Point cloud
	Processed point cloud

	WreckSight
y	Digital surface model
	Stereoscopic render
y	3D printed physical model

Would like to see more rendered 3D data. But this is very expensive to process multibeam point cloud data to this stage because of the noise and amount of holes in the data.

B5 Which of these different visualisation stages would you like to see used **less** often as deliverables and why? *(Please select any that apply and provide further information on your reasons for these choices in the text box below.)*

	Raw data
	Point cloud
	Processed point cloud
	WreckSight
	Digital surface model
	Stereoscopic render
	3D printed physical model

C1 What attributes or features do you think define **good quality** subsea survey data?

Accuracy of data and calibrations. Data lines up between different survey lines.

C2 What attributes or features do you think define **bad quality** subsea survey data?

Mis-align between survey lines. Noise in data from poor cleaning or incorrect settings during acquisition.

C3 What are the biggest challenges you face when working with subsea survey data?

Precise control of acquisition platform. E.g. vessel heading drifting, line keeping and high speed.

D1 Are you aware of any guidance on best practice, including the use of metadata or paradata, when working with subsea survey data? *(If 'yes', please provide details.)*

	Yes
N	No

D2 Are you aware of any activities or standards currently used to grade or evaluate subsea survey data? *(If 'yes', please provide details.)*

	Yes
N	No

D3 How does the *Dundee Data Grading Scale* compare to other means of grading subsea survey data that you have previously used? *(If you haven't used any others, please write N/A.)*

N/A

D4 The *Dundee Data Grading Scale* is designed to make it easier to identify and compare the quality of subsea survey datasets. On a scale of 1 to 5, how well do you think this has been achieved? *(Please provide further information on your reasons for this choice in the text box below.)*

	1 *(not at all achieved)*
	2
	3
4	4
	5 *(fully achieved)*

It seems like a good way of instantly comparing data sets of differing quality.

D5 What do you think are the **advantages** and **disadvantages** of using the *Dundee Data Grading Scale* to grade and compare subsea survey datasets?

Basic 5 point grading may miss details.

D6 What do you think of the **selection**, **ordering** and **relevance** of the grading criteria used by the *Dundee Data Grading Scale*? Are there any that you would change?

No

D7 How would you **improve** the *Dundee Data Grading Scale*?

Possibly with some screenshots of the data next to each grade assessment.

14.5 Appendix V: Examples of data grading systems

Army rank insignia (or 'emblems of authority')

A means of identifying military rankings and hierarchy. For example, in the British Army, this includes titles such as *Private*, *Corporal* or *Sergeant* (British Army, no date).

Beaufort wind force scale

An empirical measure that relates wind speed to observed conditions at sea or on land. For example, a score of '0' represents calm conditions, and '12' is representative of a hurricane (where the wind speed is 64 Knots or greater) (Encyclopædia Britannica, 2017).

Blue Flag beaches

Defined standards for quality, safety, environmental education and information, the provision of services and general environmental management criteria. The Blue Flag is sought for beaches, marinas, and sustainable boating tourism operators as an indication of their high environmental and quality standards (Foundation for Environmental Education, no date).

Bortle Scale

A nine-level numeric scale that measures the night sky's brightness of a particular location, where a score of 9 represents an '*inner-city sky'* and 1 is described as an '*excellent dark-sky site*' (Bortle, 2001).

Bristol Stool Scale

A diagnostic medical tool designed to classify the form of human faeces into seven categories, with Type 1 and Type 7 representing constipation and diarrhoea, respectively (Lewis and Heaton, 1997).

British Standards Institution

BSI is the national standards body of the UK, and produces technical standards on a wide range of products and services, and also supplies certification and standards-related services to businesses. The most recognisable of these is the *Kitemark™*, which signifies products or services which have been assessed and tested as meeting the requirements of the related specification or standards (BSI, no date).

British undergraduate degree classification

A grading structure for undergraduate degrees or bachelor's degrees (and integrated master's degrees) in the UK. Examples of this include '*First Class Honours*', which is awarded to those with the highest academic achievement.

Decibels

The decibel (symbol: *dB*) is a unit of measurement used to express the ratio of one value of a physical property to another on a logarithmic scale (Lexico, no date-a). For example, a normal conversation is rated as around 60 dB, where a bus interior is 90 db and amplified rock music is 120 db (Encyclopædia Britannica, 2020).

Douglas Sea Scale

Used to measure the state of the sea and the swell of waves, expressed in one of ten degrees. For example, Degree O is described as both "calm sea" and "no measurable wave height (Encyclopedia.com, 2020).

Energy Performance Certificate

A list of statistics about the energy efficiency of your home, with recommendations. An award rating of 'G' suggests a lack of energy efficiency (and therefore higher running costs), where an 'A' rating is considered very energy efficient (Scottish Government, 2016).

Forel-Ule Scale

A method to approximately determine the color of bodies of water, used in limnology and oceanography. Mixing a variety of chemicals produces a standard color scale in a series of numerically designated vials (1-21), which are then compared with the color of the body of water to aid in classifying gross biological activity (Novoa et al., 2014).

Fujita scale

For rating tornado intensity, based primarily on the damage tornadoes inflict on human-built structures and vegetation. A score of 'F0' is described as the observation of '*light damage*' and wind speeds of 40-72mph, whereas a result of 'F5' represents '*incredible damage*' and wind speeds of 261-318mph (Fujita, 1971).

Hamilton-Norwood Scale

For classifying the progression of male pattern baldness. A series of seven images and descriptions present each stage, from very minor recession of the hairline to only a narrow horseshoe-shaped band of hair remaining (Norwood, 1975).

Hynek Scale

A six-item system for classifying UFO sightings and alien contact, arranged according to increasing proximity. These include three categories of 'close encounter' and were referenced in the 1977 film *Close Encounters of the Third Kind* (Hynek, 1972).

Kardashev Scale

A method of measuring a civilization's level of technological advancement, based on the amount of energy a civilization is able to use for communication. The theoretical scale has three designated categories: Type I (planetary civilisation), Type II (stellar civilisation), and Type III (galactic civilisation). Earth is considered to have not yet met the requirements in becoming a Type I civilisation (Kardashev, 1964).

Kinsey Scale

Used to describe a person's sexual orientation based on their experience or response at a given time. The scale typically ranges from 0, meaning exclusively heterosexual, to 6, meaning exclusively homosexual (Kinsey et al., 2003).

Mach number

Defined as the ratio of the speed of an object to the speed of sound in the same medium. *Mach 1* indicates the speed of sound, where *Mach 2* would be twice the speed of sound (supersonic flight is considered to be in the range of *Mach 1.2-5.0*) (Encyclopædia Britannica, 2019).

Modified Mercalli intensity scale

For measuring the intensity of an earthquake (based on observed effects). The measurements range from *I. Not felt*, to *XII. Extreme* (Wood and Neumann, 1931).

MI5 Threat Levels

Designed to give a broad indication of the likelihood of a terrorist attack, covering 5 levels – *low*, *moderate*, *substantial*, *severe* and *critical* (MI5, no date).

Michelin Stars

A method of assessing and grading restaurants on their quality, using a framework of zero, one, two and three stars. There are currently just five restaurants in the UK which hold the coveted three-star award (MICHELIN Guide, no date).

Mohs scale

Based on the abilities of natural minerals to scratch one another. A numerical scale, from 1-10, grades mineral hardness, where diamonds are classed as 10 (Frost, 1981).

Palermo Technical Impact Hazard Scale

A logarithmic scale used by astronomers to rate the potential hazard of impact of a near-earth object (NEO). A rating of 0 means the hazard is considered a *background hazard*, and a rating of +2 would indicate the hazard is 100 times more likely than a random background event (Chesley et al., 2002).

pH

A numeric scale used to specify the acidity or basicity of an aqueous solution. Ranging from 0-14, solutions with a pH less than 7 are *acidic* and solutions with a pH greater than 7 are *basic* (Covington et al., 1985).

Richter magnitude scale (later Local magnitude scale or ML)

For measuring the strength ("size") of earthquakes, using a scale ranging from 1-10 where each whole number represents a tenfold increase in magnitude (Richter, 1935).

Saffir–Simpson hurricane wind scale

Classifies hurricanes by the intensities of their sustained winds, based on a scale from 1-5, where categories 3 and higher are considered major hurricanes because of their potential for significant loss of life and damage (Taylor et al., 2010).

Scoville Scale

A measurement of the pungency (spicy heat) of chili peppers, or other spicy foods – a numerical Scoville score is calculated for each type of food (Scoville, 1912). Examples include bell peppers (0), jalapeño peppers (2,500-8,000), Ghost Peppers (800,000-1,001,300) and the Carolina Reaper (2,200,000) (Chili Pepper Madness, 2019).

Temperature

A physical quantity expressing hot and cold, which can be measured using different and corresponding scales – *Celsius*, *Fahrenheit* or the SI base unit of temperature, *Kelvin* (BIPM, 2019).

Torino Scale

For categorizing the impact hazard associated with near-Earth objects (NEOs) such as asteroids and comets. An integer scale from 1-10 is used, where 1 represents a negligibly small chance of collision and 10 indicates that a collision is certain (NASA/JPL, 2005).

Ulmer Scale

A 100-point method to quantify a star's '*bankability*' or value to a film production, in terms of getting a movie financed and the cameras rolling (e.g. *A-list*, etc.) (The Ulmer Scale, no date).